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Greenhouse gas footprints of different biofuel production systems

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ABSTRACT

The aim of this study is to show the impact of different assumptions and methodological choices on the life-cycle greenhouse gas (GHG) performance of biofuels by providing the results for different key parameters on a consistent basis. These include co-products allocation or system expansion, N_2O emissions from crop cultivation, conversion systems and co-product applications and direct land-use change emissions. The results show that the GHG performance of biofuels varies depending on the method applied and the system boundaries selected. Key factors include selected allocation procedures and the location of production and related yields, reference land and soil N_2O emissions.

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1. Introduction

The impact of the replacement of conventional transportation fuels by biofuels on greenhouse gas (GHG) emissions and fossil energy use is subject of fierce debate. Life-cycle Assessments (LCAs) come to widely ranging conclusions that are the results of differences in (data) quality, the setting in which production is assumed to take place, the method used to account for co-products and the assumptions on changes of above- and belowground biomass, soil organic carbon, litter and dead wood due to (in)direct land-use change [1,2]. Also the choice of reference system is an important aspect if energy and GHG emission credits are given to the use of co-products as animal feed or energy [3,4]. Several studies have suggested that the use of protein-rich by-products from grain ethanol manufacture as animal feed may play a large role in offsetting (in)direct land-use change effects and related GHG emissions [5]. Overall, calculating the performance of biofuels on GHG emissions and fossil energy use is difficult, due to the large number of, partially uncertain, parameters and impacts, as well as methodological issues. The goal of this study is to investigate the energy requirements and GHG emissions of various transportation biofuels relative to conventional fossil fuels for the current situation and specific cases for the future.

The goal of this study is to investigate the GHG and energy balance of biofuels using a consistent set of system boundaries in time and space so that the results of each chain are comparable. Specific attention is paid to the implications of selecting different reference systems for land use and related changes in carbon stocks, use of co-products and allocation methods, the selected time period and the emissions of nitrous oxide (N_2O) that are caused by changes in land use and by the use of nitrogen fertilizers.

A wide range of energy crops and conversion technologies can be used to produce biofuels. We have selected the most commonly used combinations of energy crops, conversion technologies, and key producing world regions or potentially promising world regions (Table 1). Data are derived from recent, state-of-the-art life-cycle studies on biofuel production chains that that report underlying assumptions and procedures used for allocation and reference systems transparently. The main references are shown in Table 1. Details on these production routes can be found in Appendix B.

Differences between regions are incorporated by differences in crop yield, soil conditions and fertilizer application rates. The performance of conversion technologies is assumed the same across all regions, unless indicated otherwise.

Section 2 describes the methodology, the methodological aspects and assumptions that are included. Section 3 shows results for the energetic and GHG performance of the biofuel production systems considered for different methodological choices and input variables. In Section 4 the results are discussed and Section 5 finalizes with the conclusion. Detailed input and result data is provided in the appendices.

2. Methodology

The energy and greenhouse gas balances are quantified and compared to the fossil reference system as described in Fig. 1. The biofuels production chains are divided in four processes: (i) biomass production or cultivation, (ii) pre-treatment, storage and transport of the bioenergy crops to the conversion plant, (iii) conversion of bioenergy crops to biofuels and (iv) transport and distribution to gas stations.

Detailed calculations are included to estimate the GHG emissions and energy use of the different production steps of the biofuel and conventional fuel chains considered (following Bergsma et al. [6]).

For biofuels production, the following energy use or emission categories are distinguished:

- Biomass production:
  - The production of fertilizers.
  - The production of agro-chemicals.
  - The use of fertilizers. Nitrous oxide (N_2O) emissions are thereby crucial, as further discussed in Section 2.7.
  - The transportation of the feedstock to a biofuels production plant.
- Biomass production induced direct or indirect changes in land use. Biomass to biofuels conversion:
  - The use of energy for biomass pre-treatment.
  - The use of energy for the conversion of biomass to biofuels. A crucial issue is the methodology that is used to include co-products from conversion, see further Section 2.4.
  - The production of chemicals.

Table 1
Selected biofuels and corresponding energy crops, conversion technology, key producing regions and the fossil-oil-based reference fuel.

Biofuel type	Energy crop	Key producing regions	Conversion technology	Reference fuel	Main references
Ethanol	Maize	US, West Europe, East Europe	Fermentation	Gasoline	[4,11,22]
Ethanol	Wheat	US, West Europe, East Europe	Fermentation	Gasoline	[4,11,22]
Ethanol	Sorghum	US, West Europe, East Europe	Fermentation	Gasoline	[44]
Methyl ester	Palm fruit	South-East Asia	Transesterification	Diesel	[4,11,22,26]
Methyl ester	Rapeseed	West Europe, East Europe, Canada	Transesterification	Diesel	[4,11,22]
Ethanol	Sugar cane	Brazil	Fermentation	Gasoline	[22,31]
Ethanol	Sugar beet	West Europe, East Europe	Fermentation	Gasoline	[4,11,22]
Methyl ester	Soybean	US, Brazil	Transesterification	Diesel	[4,11,22]
Methyl ester	Jatropha	Africa, India	Transesterification	Diesel	[11,45]
Ethanol	Switchgrass	US, West Europe, East Europe	Hydrolysis & Fermentation	Gasoline	[11,46]
Ethanol	Miscanthus	US, West Europe, East Europe	Hydrolysis & Fermentation	Gasoline	[11,46]
Ethanol	Eucalyptus	Brazil	Hydrolysis & Fermentation	Gasoline	[11,47]
FT-diesel	Switchgrass	US, West Europe, East Europe	Gasification & FT-synthesis	Diesel	[11,46]
FT-diesel	Miscanthus	US, West Europe, East Europe	Gasification & FT-synthesis	Diesel	[11,46]
FT-diesel	Eucalyptus	Brazil	Gasification & FT-synthesis	Diesel	[11,47]

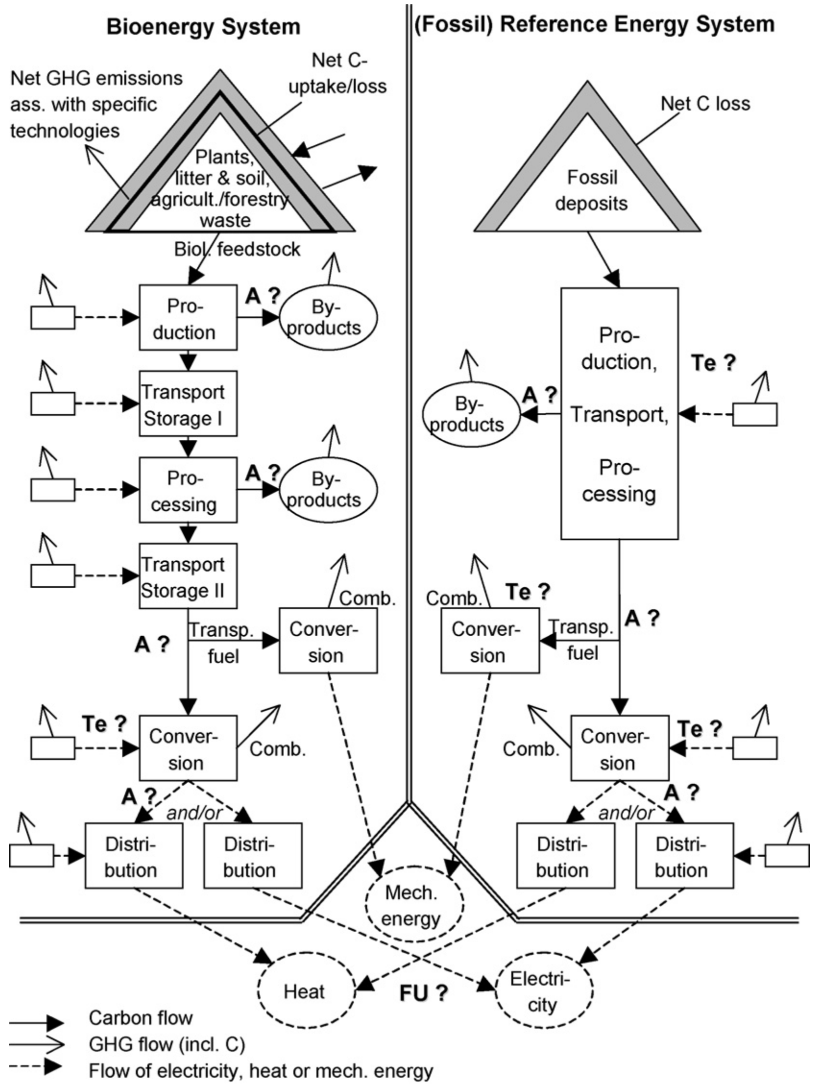

Fig. 1. The bioenergy and reference system as graphically presented in [20]. The question marks indicate examples of special methodological interest for allocation methods (A?) of which four are applied in this study, choice of functional unit (FU?) and choice of technology (Te?).

For the fossil reference systems, the following emissions are taken into account:

- emissions from mining/extraction;
- emissions from transport;
- emissions from conversion to primary energy carrier; and
- emissions from distribution and end use.

Specific attention is paid to the impact of direct and indirect changes in land use and the resulting impact on GHG emissions from changes in above- and belowground biomass, soil organic carbon, litter and dead wood and on N_2O emissions, but also to the methodology used to include co-products from conversion. Several other parameters are also varied to investigate the impact of uncertainties and different production chains on the results, such as the type of energy used during conversion, the fertilizer application rate, the transportation distance, etc.

The life-cycle performance of fossil gasoline and diesel in the Europe is derived from the JEC WTW study [4] based on data from CONCAWE. The GHG and energy balances are also used as starting point in the calculations and are supplemented with other data sources.

2.1. System boundaries and functional units

2.1.1. Functional unit

For this study, two functional units for comparison are used. The functional units for energetic performance are MJ_{prim}/MJ_{fuel} and MJ_{prim}/ha land. For the GHG mitigation performance the functional units are g CO_2 equiv./MJ_{fuel} and g CO_2 equiv./ha land. The biofuel substitutes considered in this study have similar combustion characteristics compared to conventional fossil fuels. This justifies a direct comparison of fuels based on their calorific value.

2.1.2. Energy and greenhouse gas balances

This study considers the significant GHGs for biofuel production: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). A 100-year time horizon is considered for the global warming potential (GWP) of these GHGs based on the fourth assessment report of the IPCC [7]. The GWP is 1, 25 and 298 for CO_2, CH_4 and N_2O, respectively.

The GHG reduction potential is calculated relative to the fossil references (diesel and gasoline):

$$\text{GHG} = \frac{\text{GHG emission fossil chain} - \text{GHG emission biochain}}{\text{GHG emission fossil chain}} \quad (1)$$

The demand for energy utilities for feedstock production, transport or biofuel production are expressed per unit of energy delivered, i.e. the energy that is used by the consumers. The measure for the energetic performance of the biofuel and fossil reference systems in this study is primary energy which is the total amount of energy available in the natural state of these fossil resources [8]. Unless stated otherwise, all energy units in this study are expressed in lower heating value (LHV).

2.2. Time horizon and time factor

This study includes first-generation biofuels that are currently being produced on commercial scales, but also second-generation biofuels that are not yet produced commercially at a large-scale, such as ethanol from lignocellulosic biomass and synthetic diesel. Results are generated for the present situation and in specific cases also for the future.

Time is also an important factor in calculations of the annual life-cycle performance of biofuels. Both energy inputs and outputs and emissions occur at different points in time. For example emissions from land use due to changes in aboveground biomass occur mainly during the short period when the land is converted for cultivation. The chosen time scale for amortization of these emissions can change the results drastically. In this study, specific attention is paid to the timeframe across which the changes in the above- or belowground biomass, soil organic matter, litter and dead wood. For example, the IPCC uses a default value of 20 years [9], while Greenpeace aims for a 10-year period [10].

2.3. System boundaries

The focus in this study is on the GHG emissions and fossil primary energy use of biofuels and conventional fuels. Biofuels are assessed by taking into account the energy requirements and GHG emissions from the production of resources (cradle) to the final end use phase (grave), i.e. including the production of the feedstock, the conversion of the feedstock into biofuels and the transportation of the biofuels to Western Europe. Both direct and indirect GHG emissions and fossil primary energy use are considered. Direct emissions are emissions that occur at energy conversion or utilization processes or due to the direct effects of land-use changes. Indirect emissions are emissions that occur upstream from the production of utilities and raw materials utilized for the production of biofuels or occur due to the indirect effects of land-use changes. Emissions that occur from the construction, operation and maintenance of equipment and infrastructures related to biofuels production, i.e. third order emissions, are not taken into account in this study.

2.4. Co-products

The production of biofuels often results in the production of large quantities of co-products. For example, for the production of 1 kg ethanol from maize using dry milling, 1.25 kg DDGS (Destiller's Dried Grain with Solubles) is co-produced [11]. DDGS can be used for animal feed, but also for energy purposes, e.g. via anaerobic digestion. Another example is the production of diesel from soybeans, which co-generates 4.2 tonne of dry soy meal (generally used as animal feed) per tonne of diesel [12]. A list of co-products and their applications assumed in this study are given in Appendix A.

The way in which co-products from biofuel production are included in the LCAs is a crucial factor [2,13]. Two main approaches are commonly applied in LCA studies:

1. *Allocation*, whereby the emissions due to energy crop production and processing are (partially) allocated to the co-products of biofuel production on the basis of either: *weight*, *energy content* or *market value* of these products. The advantage of the first two is that they are relatively easy to apply and allocation factors do not change over time like economic indicators or substituted product types do. The default and typical values reported in the draft proposal "Directive on the promotion of renewable energy", as published in January 2008, are based on allocation based on energy basis for co-products and subtraction for co-generation of heat and electricity. The main disadvantage is that this method does not accurately reflect the real impact of the use of co-products.
2. *System boundary expansion*. Allocation can be avoided by taking account of the emissions that are avoided when the co-products replace other products. This approach is also recommended by the guidelines for LCA issued by the International Organisation for Standardization ISO 14040-14049 guideline series [14]. A disadvantage of this methodology is that it increases the scope of the LCA study, as it requires an estimation of the avoided emissions.

In this study both allocation (mass, energy content and market value) and system expansion approach are applied to account for co-products.

2.5. Direct and indirect land-use change

Direct land-use change occurs when bioenergy crops are cultivated on land that was previously not used for cropland or farming. This includes natural vegetation areas such as forests, but could also be set aside land or degraded land. Indirect land-use change occurs when the previous activity which used the land previously shifts to other land induced by crop production for bioenergy purposes. These effects are also known as 'leakage' or 'displacement' as they occur outside the system boundary, but can be allocated to action that occurs within the system [15,16]. Both direct as indirect land-use change can have a significant impact on the GHG balance of biofuels, due to the GHG emissions from changes in above- and belowground biomass, soil organic carbon, litter and dead wood [10,17–19].

2.5.1. Direct land-use change

Changes in above- and belowground carbon per hectare of bioenergy crop are estimated for the five carbon pools that defined by the IPCC: above- and belowground biomass, soil organic carbon, litter and dead wood. The total change in carbon stock is calculated using Eq. (2) [20]:

$$\Delta\text{Carbon stock soil}\ \ (\text{tC/ha}) = \sum_i \text{Carbon stock change factor}$$
$$(\text{t/ha year}) \times T_{\text{i}}(\text{year}) \tag{2}$$

The methodology and data to estimate the changes in the above- or belowground biomass, soil organic matter and litter are taken from the literature, whereby the IPCC Guidelines for National Greenhouse Gas Inventories [9] are used as starting point. The IPCC approach is compared with data and methodologies from other sources e.g. [10,17,18].

2.5.2. Indirect land-use change

Indirect land-use change effects are difficult to estimate as it requires a detailed understanding of the dynamics of agricultural markets and agricultural land use. Most studies use general or partial equilibrium models to analyse the dynamics of commodity prices, land availability and sectoral changes as a

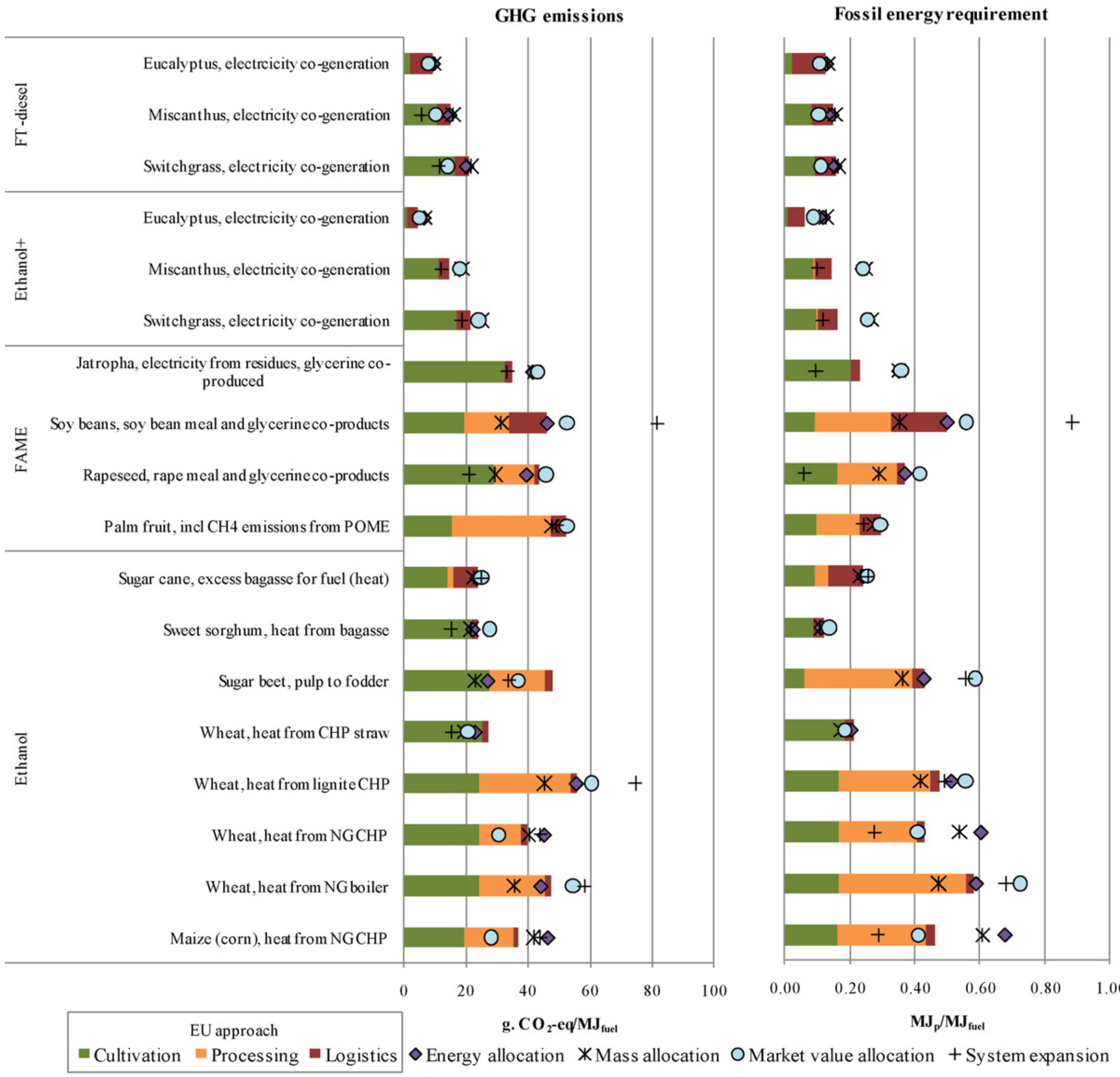

Fig. 2. Fossil energy requirement and GHG emissions from biofuel production for the base cases. Allocation of co-products by EU default (energy allocation for co-products, subtraction for co-generation of electricity and heat), energy, mass and market value. No reference land use selected (no LUC). JRC DNDC model for N_2O emissions from sugar cane, wheat, sugar beet, maize and rapeseed. IPCC model for miscanthus, palm fruit, soy beans, switchgrass, eucalyptus and jatropha.

result of bioenergy production [15]. However, this method is also being criticized. Hutchison et al. [16] claim that the limitations of forecasting models as a result of uncertainties in degrees of freedom in forecasting, feedback loops and interaction complexity result in model outcomes that do not generate policy relevant information and lacking evidence. Alternative suggested methods are, amongst others, the risk adder approach [21] and the approach from Ecometrica [16]. In case of the risk adder approach, a default conservative value was estimated for the conversion of a high carbon content natural system to arable land of 300 t CO_2/ha and a time frame of 20 years. This results in 15 t CO_2/(ha year) of which 25% or ~4 t CO_2/ha has to be allocated to biofuels annually from a German perspective.[1] The method suggested by Ecometrica is based on the land-use changes reported by the FAO between 2000 and 2005 and allocation of marginal increases in output. They calculated the indirect effect at 0.286 t CO_2/t crop additional production[2] of which part is allocated to by-products by energy content. By using the same land-use change emission factor for all biofuel production systems, i.e. allocating land-use change emissions equally to all biofuels, different yields of energy crops are neglected. This factor might therefore be more negative for second generation fuels with limited co-products produced and higher yields per ha because this method does not take differences in yield into account.

This study does not suggest a method for indirect land-use change emissions. Rather we explore the impact of some scenarios including direct land-use change effects and the impact per type of biofuels.

[1] 50% will be second generation biofuels from residues (no leakage), 50% of energy crops will be produced on former set aside land resulting in 25% of energy crop production that induces displacement of land indirectly [21].

[2] According to the FAO, 16% of deforestation effects can be allocated to agricultural activities. Hutchison et al. [16] estimate the contribution of biofuels based on the total feedstock fraction from agriculture used for biofuels between 2000 and 2005 (6.6%) resulting in 124 Mton CO_2 equiv. Based on the increase in crop output between 2000 and 2005 (263 Mton), the GHG emissions from deforestations allocated to agricultural activities in this period (11,777 Mton CO_2). 11,777 Mton CO_2 × 16%/263 Mton additional feedstock × 25 years.

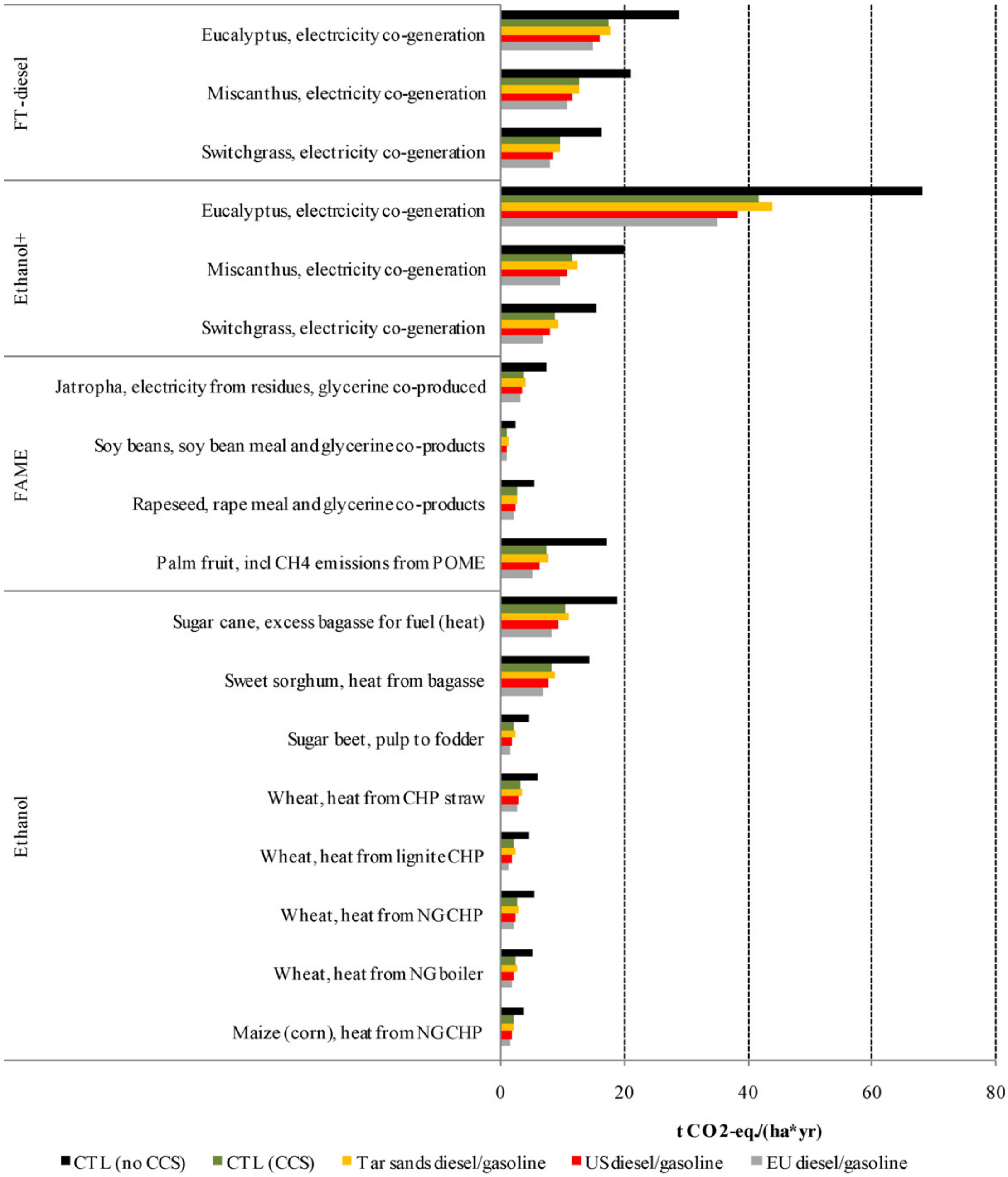

Fig. 3. Life-cycle greenhouse gas emissions saved per hectare land for different fossil reference fuel types: for the EU [11], the US (GREET [40]), Canadian tar sands [41], coal to liquids with and without carbon capture and storage [42]. Input assumptions similar to the EU method for allocation of Fig. 2.

2.6. Emissions from fertilizer use

In this study data on the N_2O emissions from bioenergy crop production will be calculated using:

- The results of the JEC WTT study [11] which are based on the DNDC model for N_2O emissions, of which the results are also included in the in the EU "Directive on the promotion of renewable energy"
- The IPCC Tier 1 method for fertilizer induced emissions (FIE). Most biofuel LCA-studies apply the Tier 1 method from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [9] to account for direct N_2O emissions from fertilizer application. This method assumes that 1% of the N input from N-fertilizers and manure result in N_2O-N emissions. This approach is based on fertilizer–induced emission (FIE). FIE is defined as the direct emission from a fertilized plot, minus the emission from an unfertilized control plot (all other conditions being equal to those of the fertilized plot), expressed as a percentage of the N input.
- The spatial explicit method developed by Smeets et al. [22]. The IPCC Tier 1 approach for direct emissions largely ignores the variability of emissions caused by differences in environmental conditions, crop type and its management. Furthermore, the FIE represents the anthropogenic emission caused by N application, although the emission from control plots may differ from the emission of the original vegetation in pre-agricultural times. The

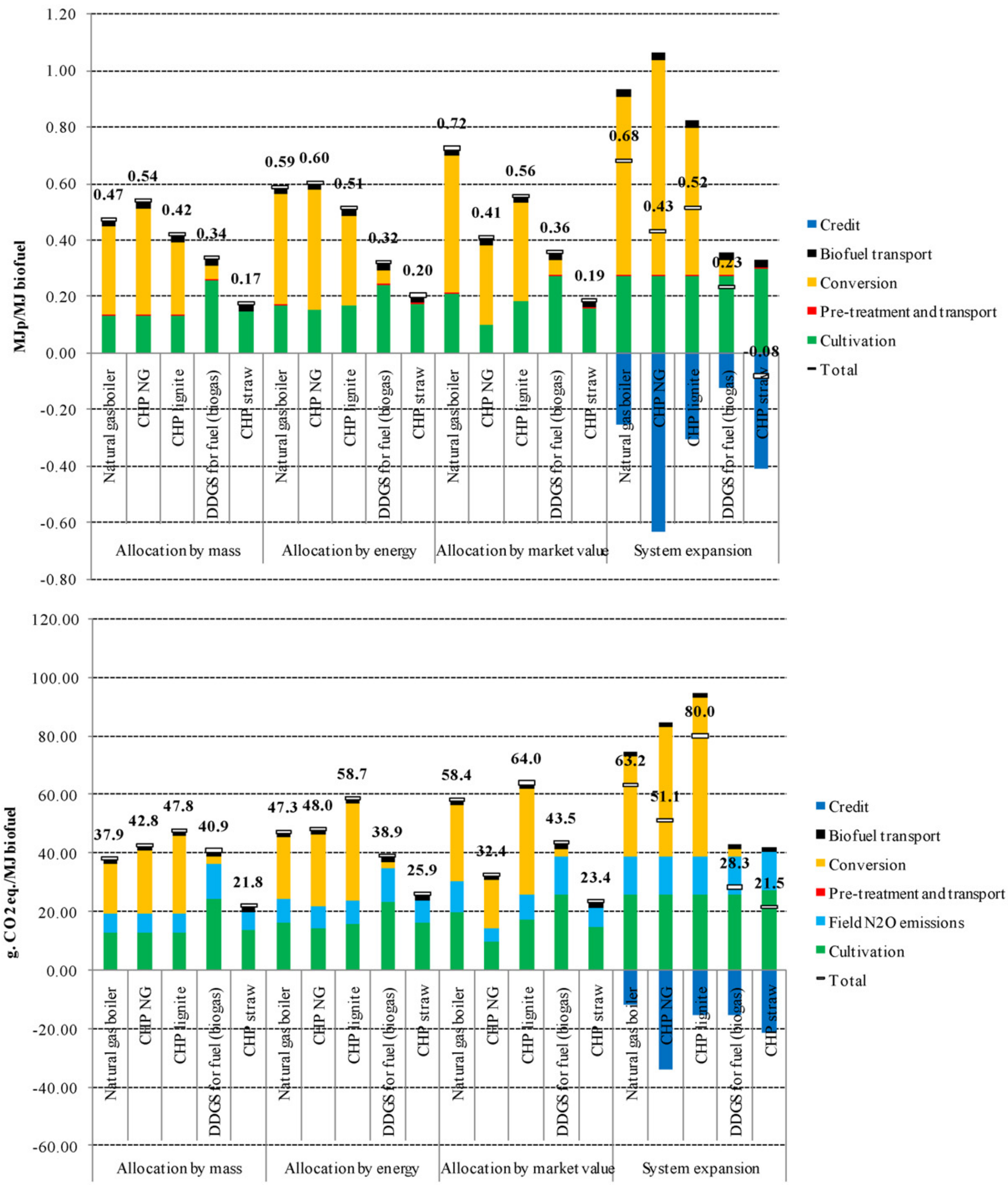

Fig. 4. Ethanol production from wheat (EU, dry milling) with DDGS used for fodder and for process heat and electricity, DNDC model for N_2O emissions. The results for other locations and for other biofuel production systems are given in Appendix B.

N_2O emission from zero-fertilizer plots may exceed that from soils under natural vegetation. In other cases it may be lower; for example, when cropland replaces tropical rainforest [23]. Smeets et al. [22] calculated the N_2O emissions from various reference land-use types and land used for the cultivation of 1st generation bioenergy crops.

2.7. Fossil references

Similar to land-use change, allocation of energy and emissions of the refinery processes to fossil fuels is based on arbitrary allocation principles [4]. Moreover, there is a wide range in the GHG and energy performance of crude oil from different sources. As easily accessible oil reserves become scarcer, oil extraction processes that require more energy and emit more GHG emissions are becoming more important. An example is that use of tar sands in Canada, which leads to higher emissions than high quality conventional oil resources [24]. In addition to conventional oil, this study includes two non-conventional sources of liquid fossil fuels: oil from tar sands in Canada and FT-diesel from coal (CTL). No assumptions were made on future marginal production scenarios.

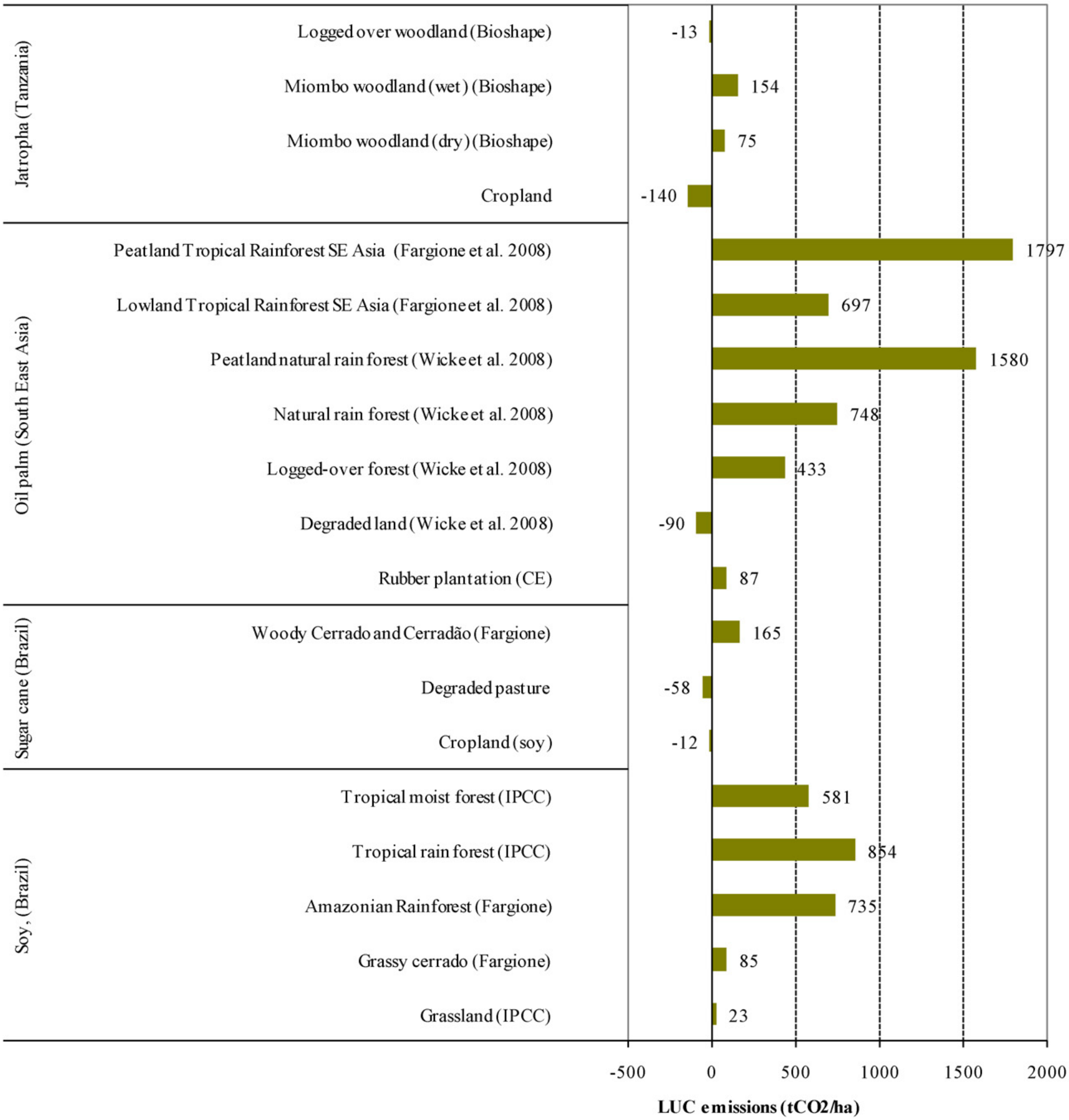

Fig. 5. Net GHG emissions due to land-use change. Based on IPCC [9], Fargione et al. [18], Wicke et al. [26], Bioshape [10]. For emissions from peatland, 20 years of emissions were allocated to land-use change due to palm oil production whereas Wicke et al. [26] assume 25 years and Fargione et al. [18] assume 50 years.

3. Results

3.1. Biofuel production

For each biofuel chain, the base case results are calculated. These are consistent with the JEC methodology and background data [4,11] including allocation for by-products by energy content. The results are displayed in Fig. 2 and Appendix B. This reference is selected because it is also used to calculate the default and typical values (plus underlying assumptions) as reported in the "Directive on the promotion of renewable energy"[3] [25]. It should be noted however that the EC database is updated when more up-to-date figures are available. Later and earlier versions of the default values in the directive might therefore be different from the results presented in this report (Fig. 3).

3.2. By-product use and allocation

Fig. 4 shows the GHG and energy requirements for ethanol production from wheat in the EU. These results are exemplary to show the variation in biofuel production chains, use of co-products and allocation procedures. Process heat and electricity are generated from natural gas (boiler or CHP plant), a lignite CHP plant, biogas from anaerobic digestion of DDGS or straw combustion. In case of straw combustion, additional fertilizers are required. In case of DDGS for energy purposes, the residues are used for fertilizers. These options are based on JEC [4,11].

[3] The EC default and typical GHG values for biofuel production are updated when more accurate or up-to-date data is available. The results, as presented in this report, could therefore differ from earlier or later versions. The most recent data can be found on: http://re.jrc.ec.europa.eu/biof/.

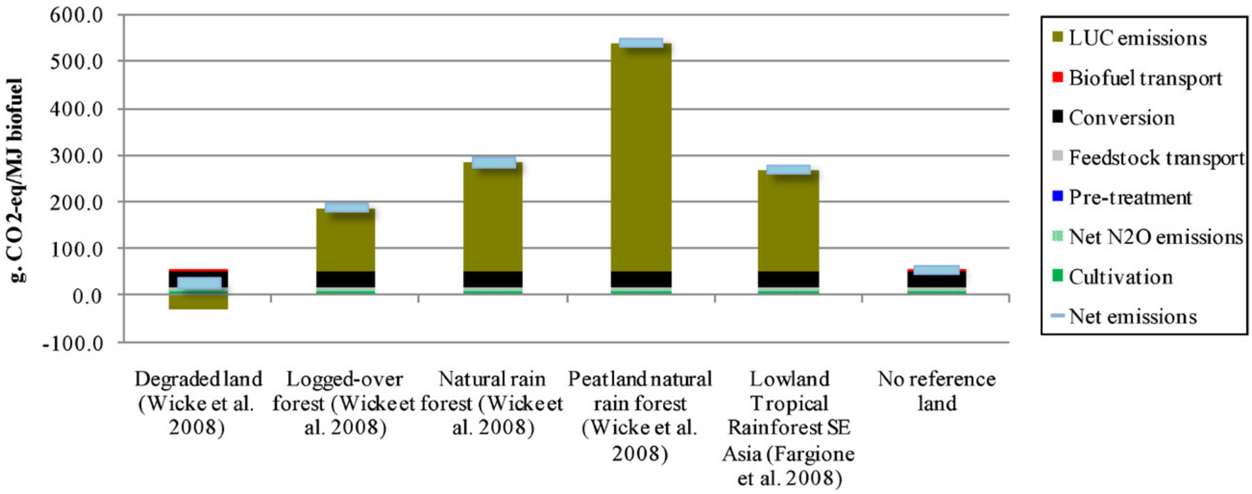

Fig. 6. Greenhouse gas emissions from palm oil biodiesel production including land-use change emissions for different land types. Years of allocation: 20.

If allocated by mass, the NG boiler system performs better than the NG CHP system as co-produced electricity cannot be allocated for on mass basis. If straw is used for process heat, the system has the best GHG and energetic performance for all allocation procedures. From an environmental perspective, it is better to use DDGS as biofuel. From an economic perspective however, the added value of DDGS is higher if it is sold as animal fodder. This is better represented by allocation by market value.

3.3. Reference land

3.3.1. Emissions from land-use change

The amount of greenhouse gases released from converting reference land into cropland for biofuel crops varies strongly per type of reference as displayed in Fig. 5. The difference in peatland emissions between Fargione et al. [18] and Wicke et al. [26] is mainly due to the years of emission accounting of 25 and 50 years in Wicke et al. [26] and Fargione et al. [18], respectively.

Soy for European markets is mainly imported from Brazil and Argentina. The current results only include production in Brazil, but results for North-America will be added in the next version. For reference land we used the IPCC Tier 1 method [9] and included data from Fargione et al. [18] for rainforest and Cerrado land as shown in Fig. 5. It depends on the allocation method and the allocation period how much is added to the GHG performance of biofuel production.

3.3.2. GHG performance including land-use change emissions

Fig. 6 shows the greenhouse gas emissions for palm oil biodiesel production for different land-use reference systems. If grown on degraded land, the carbon stored in the palm oil plantation will be higher than emitted from converting degraded land into cultivation land. If cultivation land is yielded from natural rain forests, palm oil diesel becomes a net producer of greenhouse gases for a time frame of 20 years.

3.3.3. System expansion, references for co-products

Utilization of biofuel co-products for food or feed purposes results in avoided crop cultivation and related land use. If reference land use is taken into account for biofuel crop cultivation, it should also be taken into account, reference land for co-product references should also be included.

To illustrate the impact of taking reference land for co-products into account, Fig. 7 shows the GHG performance of ethanol production from wheat and grain with DDGS either used for animal feed or for energy purposes. DDGS likely replaces Brazilian soy bean meal [4]. Substitution of soy bean meal also results in reduced soy oil production which has to be produced from sources. Marginal vegetable oil is likely to be South-East Asian palm oil, the cheapest alternative to soy oil [10,27].

Similar to Croezen and Kampman [10], we assume a worst case and best case for reference land. For the best case, maize and wheat are cultivated on former set aside land, reference land for soy bean cultivation and palm fruit cultivation is grassland and degraded land, respectively. For the worst case, maize and wheat are cultivated on former pasture land. Reference land for soy beans and palm fruit are natural rain forest and peatland natural rain forest, respectively.

The results in Fig. 7 illustrate the effect of assuming different allocation procedures and reference land types. GHG emissions from ethanol production range from −244 to 247 g CO_2 equiv./MJ biofuel for wheat and −207 to 331 g CO_2 equiv./MJ biofuel for maize. The worst cases result in such high credits for co-products as reference land for maize and wheat include relatively low levels of organic carbon whereas land-use change emissions from natural rain forest and peatland natural rainforest are extremely high (Fig. 5).

3.4. Ethanol sugar cane in Brazil

This section covers a direct comparison for ethanol produced from sugar cane in Brazil. The results of other biofuel production chains are summarized in Appendix B (Fig. 8). For both cases, we defined a default, worst and best case for the current and future (2030) situation. The assumptions are given in Table 2.

The worst, average and best case for current ethanol production and the projected performance for worst, average and best case are included. These cases are derived from Smeets et al. [28], include variable parameters for allocation methods, N_2O emissions related to sugar cane cultivation and land-use change emissions. The assumptions are summarized in Table 2.

The present, average case is based on Scenario 1 from Macedo et al. [29]. Similar to Smeets et al. [30], we assume for the worst case that no additional bagasse is available for bioenergy. For the default case, bagasse is assumed to be used for heat generation,

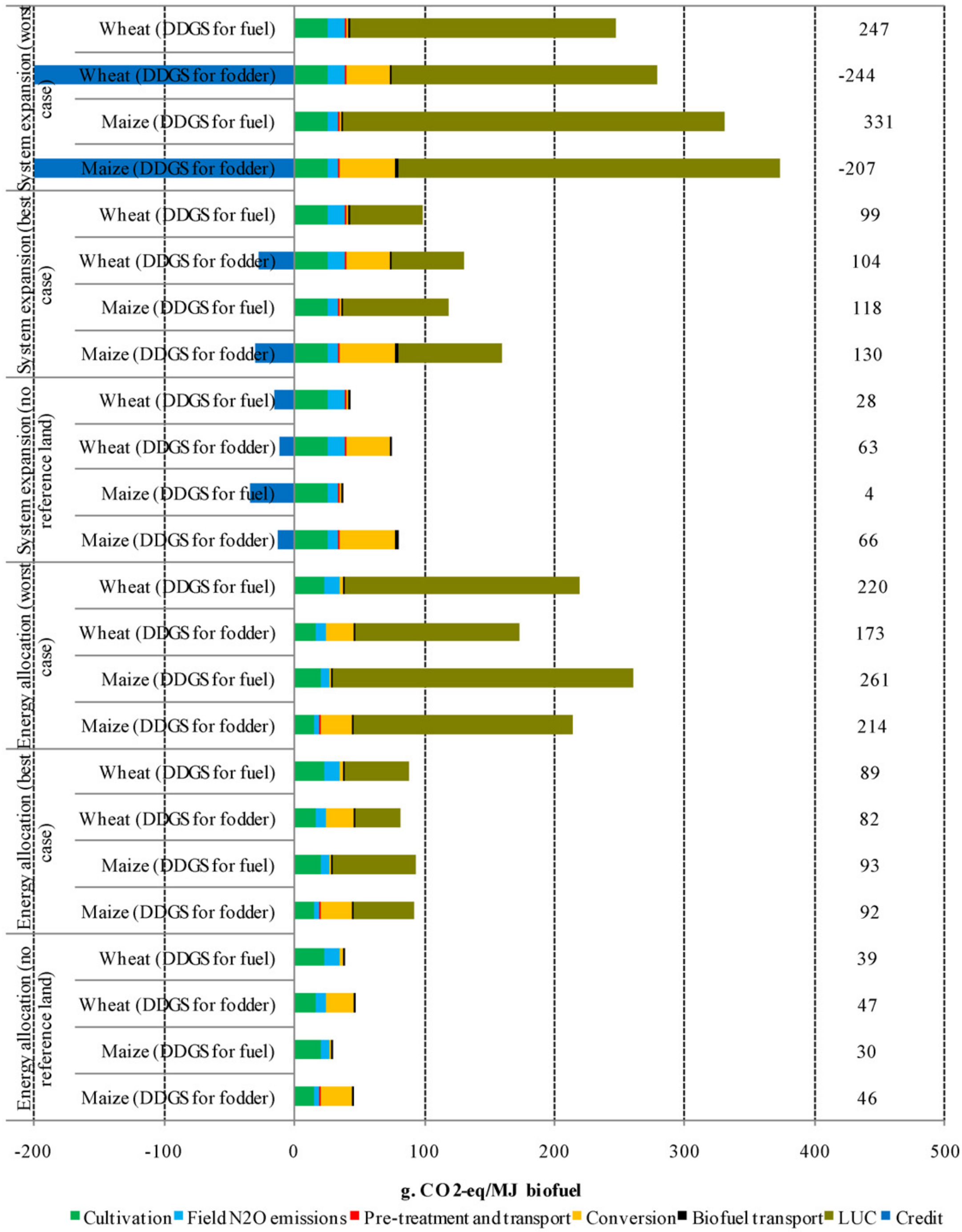

Fig. 7. GHG performance for ethanol production from wheat and maize in Europe including land-use change emissions for feedstock and for co-product references (DDGS replaces soy bean meal. The avoided soy oil production is assumed to be replaced by palm oil).

which is the current major practice in Brazil [31]. The best case is based on Scenario 2 from Macedo et al. [29].

For the future cases, we used the projections from Smeets et al. [30]. Based on an annual sugar cane yield of 100 tonne/ha (73% moist) and including 50% trash recovery which is used for electricity and heat generation.

Similar to the WTW study, we assume ethanol to be produced to the harbour by truck (700 km) where it is loaded on a product tanker for sea transport (10,186 km). Final transport to road fuel depots takes place by truck over a distance of 150 km [11].

Indirect energy and GHG emissions from the production of chemicals and utilities are calculated based on the JEC database. Results are therefore different from Macedo et al. [29]. This implies mainly higher indirect emissions for electricity for the production of e.g. fertilizers using the EU-mix instead of Brazil where 83% comes from hydropower [32].

4. Discussion

The results of this study are based on a wide range of sources for which selected methodologies are applied to calculate the

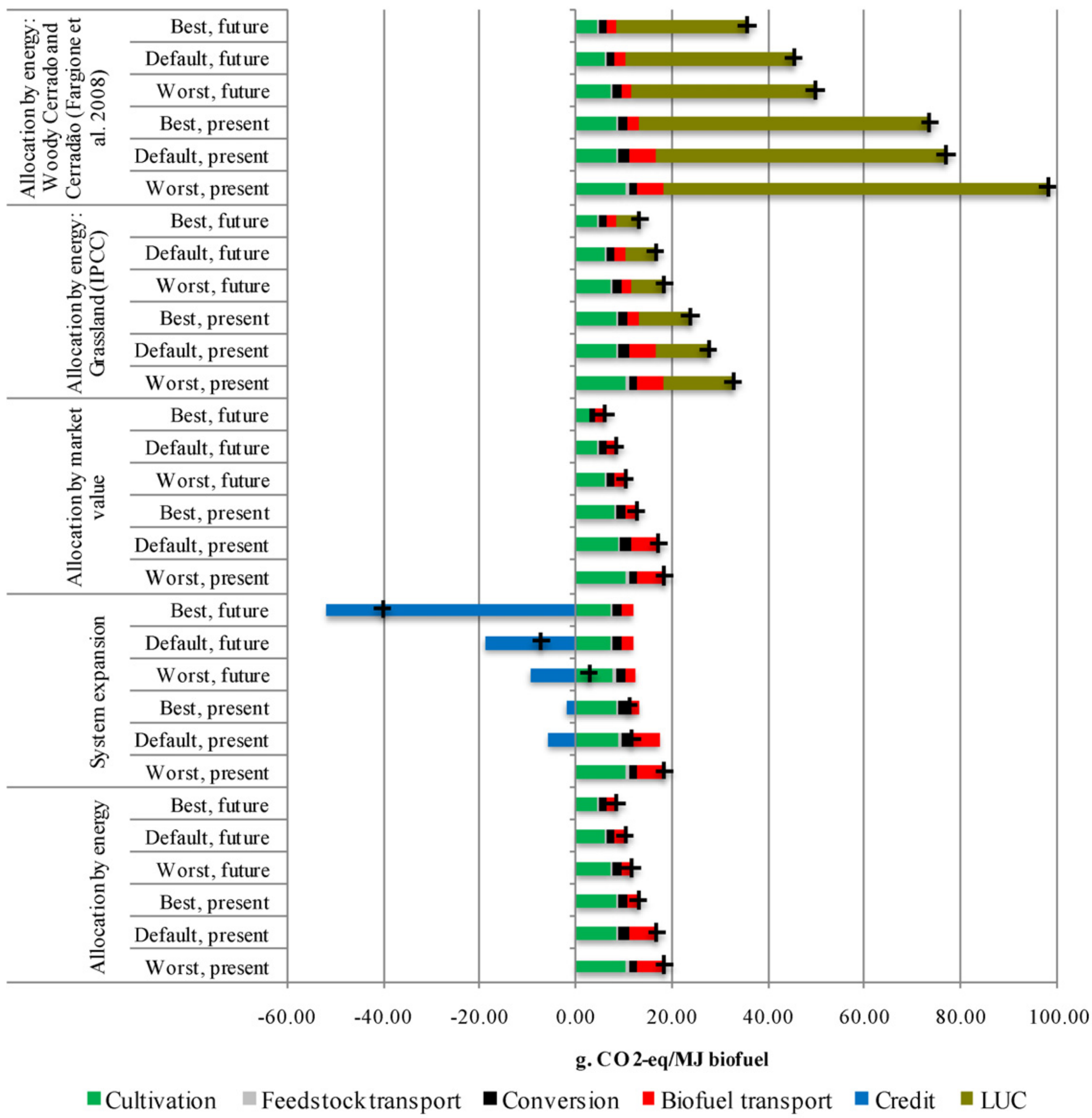

Fig. 8. Ethanol from sugar cane, Brazil. Based on [18,31,43]. Case parameters are described in Table 2, detailed results can be found in Appendix B.

life-cycle energy and GHG performance of biofuels in a consistent way. This section covers the uncertainty of the input data selected for this study, the impact of normative choices made for this study (e.g. selected conversion chains and co-product use) and the uncertainties of the methodology applied.

4.1. Input data

The emphasis of this study is on the impact of methodological assumptions for estimating the life-cycle energy and GHG performance of biofuel production systems rather than the

Table 2
Ethanol production from sugar cane, parameters for analysis.

	Present			Future		
	Worst	Default	Best	Worst	Default	Best
System	Partial cane burning	Partial cane burning	Partial cane burning	Partial cane burning	No cane burning	No cane burning
Mechanical harvesting	0.35	0.35	0.35	0.35	1	1
Trash recovery	No	No	No	No	Yes, 50%	Yes, 50%
Co-generation	N/A	Bagasse boiler	Combustion, partial steam extraction	Combustion, partial steam extraction	Combustion, partial steam extraction	Gasification, steam-injected gas turbine
Ethanol						
Yield (GJ ha^{-1} $year^{-1}$)	103.4	129.2	133.7	195.7	195.7	195.7
Yield (m^3 ha^{-1} $year^{-1}$)	4.9	6.1	6.3	9.2	9.2	9.2
Electricity surplus (kWh/TC73% moist)			10.0	59.0	110.0	300.0

absolute performance of each production chain. Input data includes a selection of state-of-the-art studies with site and chain specific data (e.g. yields, N_2O emissions, carbon stocks) reported transparently as part of the LCA calculation steps had to be repeated for this study.

4.1.1. Yields and conversion

The main source for LCA data on biofuel production was the Well-to-Wheel study from JEC [4,11] which is also used to calculate the typical and default values of the EU directive on biofuels. For ethanol from sugar cane, the updated study form Macedo et al. [31] was used whereas the JEC study [11] is based on the precursor of this study [29]. The default results for sugar cane ethanol are therefore slightly different from the results of the EU directive.

Limited data is available on the life-cycle performance of ethanol from sweet sorghum, ethanol from energy cane and biodiesel from jatropha. There is still limited experience with these feedstocks for biofuel and empirical data on the life-cycle performance of these systems is therefore scarce. For jatropha, data on crop cultivation is derived for Tanzania from Croezen and Kampman [10] with optimistic yield projections (6 Mg seeds/(ha year). It should be noted that these plantations are not yet mature and empirical studies show that yields obtained are only half of the projected yields [33].

4.1.2. Carbon stock change and reference land

Input data for above- and belowground carbon of reference land and crop land for palm oil in South-East Asia was available from [18,26], for Jatropha in Tanzania [10] and Sugar cane in Brazil [18,34]. For other crop types, the IPCC Tier 1 method was used to estimate carbon stock changes due to land-use change. Although the IPCC Tier 1 method is not site specific, the most important regions where land-use change is likely to occur are developing regions such as Brazil and South-East Asia. More detailed data is available on these areas from existing studies [10,18,26]. In Europe, set aside land or existing cropland is expected to be used for energy crop cultivation [4,10].

4.1.3. N_2O emissions from crop cultivation

For N_2O emissions from crop cultivation, three model types were used: the DNDC model results from JEC [11], the N_2O model from Smeets et al. [22] for first-generation biofuels and the IPCC Tier 1 method. For 2nd generation crops such as switchgrass, miscanthus and eucalyptus, only the IPCC Tier 1 model could be used as data on these energy crops was missing in the other model studies. Also for soy bean and palm fruit cultivation, the IPCC model was used for the JEC study. This implies that the GHG performance of all production chains can only be compared consistently using the IPCC Tier 1 model.

4.2. Normative choices and methodology

4.2.1. Chain selection and location

The selected energy crops in this study include the most commonly used energy crops, conversion routes and production locations. For the future however, also alternative crops such as algae, alternative biofuels such as hydrogen or DME, or (hybrid) electric vehicles could become important in the near future. A comparison of these chains would require a Well-to-Wheel analysis which is beyond the scope of this study.

The selected locations for dedicated crop cultivation in this study include the most common sites. Main differences per location are fertilizer use, soil properties (e.g. organic carbon) and crop yields. Site specific data on yields and N_2O emissions was available for the locations selected [22], however limited data was available on organic carbon levels and reference land per location.

4.2.2. System boundaries

For this study, system boundaries are extended to account for energy and GHG credits from the use of co-products. For all co-products, multiple end uses are defined based common practice [4]. The results are also shown if allocation methods are used rather than system expansion to show the implications of allocation procedures. It should be noted that system expansion requires arbitrary choices.

Issues arise if co-products replace products that are also produced from processes with multiple outputs. For example, if rape meal replaces soy bean meal, less soy oil will be produced. This has to be replaced with other products in which one could finally end up in endless system enlargements and modelling the world [35].

In this study, the life-cycle performances of biofuels are compared on a well-to tank basis based on the assumption that the performance of the considered biofuels and the fossil references is in range when used in internal combustion engines. Some studies indicate that ethanol blends results engine efficiencies improvements (MJ_{th}/km) up to 7.5% [36] which results in improved energetic and GHG performance of bioethanol. These factors are not taken into account in this study.

4.2.3. Time correction factor

In this study, pulse emissions from land-use change are accounted for by straight line amortization. Straight line implies that emissions that occur in the beginning have the same impact as emissions that occur at the end of the time horizon. According to the IPCC decay function of CO_2 however, 36.4% of CO_2 emitted will still be in the atmosphere after 100 years [37]. Emissions that occur at the beginning of the time period therefore have a larger impact on global warming than emissions that occur later.

In order to correct for pulse emissions that occur during initial stages of biofuel production, a time correction factor (TCF) was developed by Kendall et al. [38] based on the cumulative radiative forcing (CRF) method of the IPCC [39]. An alternative option would be to apply discount rates to GHG emissions that occur in different times. This method, however, requires the complexity of monetization of the different impacts of GHG emissions that are uncertain, even in physical quantities [38].

Both methods would result in larger impacts of emissions from land-use change on the GHG performance of biofuels, but are not considered in this study.

5. Conclusion

A life-cycle analysis has been conducted on the energy and GHG performance of different biofuel production systems from thirteen biomass feedstock types cultivated in different regions producing ethanol, biodiesel or FT-diesel. Rather than reviewing the performance parameters of biofuel production chains found, the focus of this study is on the impact of key parameters and procedures to estimate the energy and GHG performance of biofuel production chains. Included are different co-product allocation procedures, fossil energy reference systems, land-use reference systems and related land-use change emissions and carbon stock changes, site specificity and N_2O emissions from crop cultivation.

The highest biofuel yield for the biofuel production systems in this study is for ethanol from eucalyptus in Brazil (280 $GJ_{biofuel}$/ha year). The lowest yield was found for rapeseed diesel from rapeseed in East Europe (9.4 GJ $GJ_{biofuel}$/ha year). For all lignocellulosic crops (miscanthus, switchgrass and eucalyptus), yields are found to be higher than oil, sugar and starch crops.

The energy requirement for biofuel production is also lowest for FT-diesel production from eucalyptus in Brazil (−0.06 MJp/MJ biofuel) due to high crop yields, limited fertilizer inputs and credits for co-produced electricity if system expansion is applied. The highest energy requirement is for maize ethanol using a natural gas boiler if system expansion is applied (0.89 MJp/MJ biofuel). The performance of ethanol production from starch crops improves if steam is generated using CHP plants. If wheat ethanol is produced using a straw fired CHP plant, the system becomes a net producer of energy (−0.02 MJp/MJ biofuel).

No clear winner can be selected for the GHG performance of the biofuel production chains included as the performance varies considerably depending on the allocation procedure applied and the type of reference land. If emissions from land-use change are excluded, the location of crop cultivation and related yields, fertilizer application and soil N_2O emissions are key factors that determine the GHG performance of biofuel production. GHG emissions from rapeseed methyl ester (RME) can be almost twice as high as fossil diesel (140 g CO_2 equiv./MJ RME) if cultivated in East Europe and if no reference land is selected for N_2O emissions. If both rapeseed cake and glycerine are used for energy purposes and if cultivated in Western Europe, GHG emissions are 17 g CO_2 equiv./MJ RME.

It depends on the type of reference land, if the carbon content of cropland is higher or lower than the reference situation. In case of degraded land for palm fruit cultivation in South-East Asia, logged over woodland in Tanzania and degraded pasture land for soy cultivation, more carbon will be stored if the land is converted for energy crop production resulting in additional GHG credits for biofuel production. If carbon intensive land such as natural rain forest and mainly peatland natural rainforest is converted to cropland, extreme quantities of carbon will be released. If peatland natural rain forest is converted into cropland for biodiesel from palm fruit, GHG emissions are more than three times higher than from fossil diesel if allocated over 20 years.

If land-use change emissions are taken into account for co-products from energy crops cultivated in Europe, but replacing soy bean meal in Brazil, these biofuel production systems can turn out to be robust GHG savers in case of system expansion. With maize cultivated in Europe and DDGS replacing soy bean meal cultivated on former natural rain forest land, extreme credits could be allocated to ethanol production resulting in negative GHG emissions of over 244 g CO_2 equiv./MJ biofuel.

It should be noted that these cases are extreme and illustrate the impact of selected land-use reference systems rather than realistic cases. Moreover, if indirect land-use change emissions would be taken into account, a worst case scenario for the Europe would potentially be cropland that induces land-use change in similar countries of avoided land use by co-products. Nevertheless, it shows the importance of reference systems for land use and the selected procedure for co-product allocation. If allocation methods are used rather than system expansion, land-use change emissions from co-product reference systems cannot be accounted for.

In context of the current debate on the sustainability of biofuel production systems, there is a growing need to improve insight in the energetic, but specifically the GHG life-cycle performance of biofuels. This study shows that a wide variation in performance can be found for the same biofuel type depending on reference land, location of crop cultivation and related yields and soil N_2O emissions and used allocation procedure for co-products.

System expansion is the preferred method to account for co-products. However, since this method also introduces some major difficulties when e.g. reference products are also produced in multiple output systems or when the reference system cannot be identified, also other allocation procedures should be applied.

Appendix A. Co-products from biofuel production

Biofuel type	Energy crop	By-products[a]	Market price[b] (€/tonne)	Application options considered[c]	Reference product[d]	Avoided reference product kg/kg co-product
Ethanol	Maize	Cobs & stalks		Ploughed back into the field		
		DDGS	148	1) Animal feed	Soy meal	1.11[e]
					Rapeseed oil	-0.30[f]
				2) Animal feed	Soy meal	0.79[e]
					Palm oil	-0.22[f]
				3) Fuel (CHP)	CHP (nat. gas)	n/a
Ethanol	Wheat	Wheat straw	29	1) Hydrolysis & fermentation to ethanol	Gasoline	n/a
				2) Fuel (CHP plant)	CHP (nat. gas)	n/a
		DDGS	148	1) Animal feed	Soy meal	1.01[e]
					Rapeseed oil	-0.27[f]
				2) Animal feed	Soy meal	0.72[e]
					Palm oil	-0.20[f]
				3) Fuel (CHP)	CHP (nat. gas)	n/a
Ethanol	Sorghum	Pressed stalk residues		1) Biofuel (process heat)	Natural gas	n/a
				2) Hydrolysis & fermentation to ethanol	Gasoline	n/a
Methyl ester	Palm fruit	Empty fruit bunches		Organic fertilizer		
		Shells		Biofuel (process heat)		
		Palm kernel meal	55	1) Animal feed	Soy meal	0.04[g]
				2) Biofuel (CHP)	CHP (nat. gas)	n/a
		Glycerin	646	1) Animal feed	Wheat	1.00[h]
				2) Chemicals	Propylene glycol	0.79
Methyl ester	Rapeseed	Rape meal	127	1) Animal feed	Soy meal	1.07[i]
				2) Biofuel (anaerobic digestion)	Natural gas	n/a
		Glycerine	646	(See Palm fruit)		
Ethanol	Sugar cane	Bagasse	24	Heat	Diesel	
		Electricity	0.04 €/kWh	Electricity fed into the grid	National gen. mix, NGCC	n/a
Ethanol	Energy cane	Electricity	0.04 €/kWh	Electricity fed into the grid	National gen. mix, NGCC	n/a
Ethanol	Sugar beet	Leaves		Ploughed back into the field		
		Beet pulp & slop	6	1) Animal feed	Wheat	0.76[j]
				2) Biofuel (process heat)	Natural gas	n/a
				2) Biofuel (anaerobic digestion)	CHP (nat. gas)	n/a
Methyl ester	Soybean	Soy bean meal	177	1) Animal feed	Wheat	1.01
		Glycerine	646	(See Palm fruit)		
Methyl ester	Jatropha	Shell		1) Organic fertilizer	Synthetic fertilizer	
				2) Biofuel (CHP)	CHP (nat. gas)	n/a
		Seed cake		1) Organic fertilizer	Synthetic fertilizer	
				2) Biofuel (CHP)	CHP (nat. gas)	n/a
		Glycerin	646	(See Palm fruit)		
Ethanol	Switchgrass	Electricity	0.04 €/kWh	Electricity fed into the grid	National gen. mix, NGCC	n/a
Ethanol	Miscanthus	Electricity	0.04 €/kWh	(See switchgrass)		
Ethanol	Eucalyptus	Electricity	0.04 €/kWh	(See switchgrass)		
FTdiesel	Switchgrass	Electricity	0.04 €/kWh	(See switchgrass)		
FTdiesel	Miscanthus	Electricity	0.04 €/kWh	(See switchgrass)		
FTdiesel	Eucalyptus	Electricity	0.04 €/kWh	(See switchgrass)		

a) By-products come available from feedstock cultivation and harvesting and from conversion processes.
b) Hamelinck and Hoogwijk (2007)
c) The reference products are defined to allocate credits to the biofuel production chain in case of the system extension method.
d) In case there are more options for the use of by-products, the options stated in this column are included in the analysis.
e) DDGS replaces soybean meal, based on protein content of soybean meal (49%) and DDGS from wheat (39%) or DDGS maize (35%).
f) Avoided soybean meal production reduces soy oil production. This is compensated by marginal oil production (either rapeseed oil or palm oil).
g) Palm kernel meal is assumed to replace soybean meal, based on protein content of palm kernel meal (18%) and soybean meal (49%).
h) Assumed similar nutritious values.
i) Rapeseed cake is assumed to replace soybean meal, based on protein content of palm kernel meal (39.6%) and soybean meal (49%).
j) Based on protien and digestible energy content of beet pulp & slop and wheat.
k) Based on JEC 2008

Appendix B. Results

Tables A.1–A.4.

Table A.1a
Results: ethanol from maize.

	Gross energy requirement and GHG emissions				Allocation (%)			EU approach			System expansion		
					Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits		
Maize Ethanol (EU default (Romania)) Natural gas boiler													
Location: EU default (Romania), N2O model: DNDC, main references: JEC 2008													
		MJ_p/MJ_f		$g.\ CO_{2-eq}/MJ_f$	%	%	%	MJ_p/MJ_f	$g.\ CO_{2-eq}/MJ_f$	%	MJ_p/MJ_f		$g.\ CO_{2-eq}/MJ_f$
Cultivation		0.29		25.4	44%	73%	57%			57%			
N2O emissions (IPCC) DNDC			(5.4)	8.7	44%	73%	57%			57%			
Road transport, 50 km		0.01		0.5	44%	73%	57%			57%			
Ethanol plant		0.79		43.3	44%	73%	57%	0.00	0.0	57%	-0.28	-(13.4)	-13.4
Transport to depot		0.02		1.1	100%	100%	100%			100%			
Refuelling station		0.01		0.4	100%	100%	100%			100%			
Total		**1.11**	**(76.2)**	**79.4**									
Yield	GJ/ha*yr^{-1}			28									
Primary fossil energy	MJ_p/MJ_f				0.51	0.82	0.65			0.65			0.83
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f				36.1	58.7	46.1			46.1			62.8
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f				34.7	56.3	44.3						66.0
Allocation	%				44%	73%	57%			57%			
Land use change related emissions													
Pasture (CE)	Mg. CO2-eq/ha			167									
Set aside (CE)	Mg. CO2-eq/ha			46									
Allocation period:	Years			20									
Pasture (CE)	g. CO2/MJf			294	130	215	168						-580
Set aside (CE)	g. CO2/MJf			81	36	59	46						-30
Net GHG emissions (DNDC)													
Pasture (CE)	g. CO2-eq/MJf				167	274	214						-207
Set aside (CE)	g. CO2-eq/MJf				72	118	92						130
Maize Ethanol (EU default (Romania)) DDGS for biogas													
Location: EU default (Romania), N2O model: DNDC, main references: JEC 2008													
		MJ_p/MJ_f		$g.\ CO_{2-eq}/MJ_f$	%	%	%	MJ_p/MJ_f	$g.\ CO_{2-eq}/MJ_f$	%	MJ_p/MJ_f		$g.\ CO_{2-eq}/MJ_f$
Cultivation		0.29		25.4	87%	100%	79%			79%			
N2O emissions (IPCC) DNDC			(5.4)	8.7	87%	100%	79%			79%			
Road transport, 50 km		0.01		0.5	87%	100%	79%			79%			
Ethanol plant		0.03		1.5	87%	100%	79%	0.00	0.0	79%	-0.27	-(33.9)	-33.9
Transport to depot		0.02		1.1	100%	100%	100%			100%			
Refuelling station		0.01		0.4	100%	100%	100%			100%			
Total		**0.35**	**(34.4)**	**37.7**									
Yield	GJ/ha*yr^{-1}			28									
Primary fossil energy	MJ_p/MJ_f				**0.31**	**0.35**	**0.28**			**0.28**			**0.08**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f				**33.0**	**37.7**	**29.9**			**29.9**			**0.6**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f				**30.2**	**34.4**	**27.4**						**3.8**
Yield	GJ/ha*yr-1			28.38									
Allocation	%				87%	100%	79%			79%			
Land use change related emissions													
Pasture (CE)	Mg. CO2-eq/ha			167									
Set aside (CE)	Mg. CO2-eq/ha			46									
Allocation period:	Years			20									
Pasture (CE)	g. CO2/MJf			294	256	294	231						0
Set aside (CE)	g. CO2/MJf			81	70	81	63						0
Net GHG emissions (DNDC)	g. CO2-eq/MJf												
Pasture (CE)					289	331	261						331
Set aside (CE)					103	118	93						118
Maize Ethanol (EU default (Romania)) CHP lignite													
Location: EU default (Romania), N2O model: DNDC, main references: JEC 2008													
		MJ_p/MJ_f		$g.\ CO_{2-eq}/MJ_f$	%	%	%	MJ_p/MJ_f	$g.\ CO_{2-eq}/MJ_f$	%	MJ_p/MJ_f		$g.\ CO_{2-eq}/MJ_f$
Cultivation		0.29		25.4	44%	56%	56%			57%			
N2O emissions (IPCC) DNDC			(5.4)	8.7	44%	56%	56%			57%			
Road transport, 50 km		0.01		0.5	44%	56%	56%			57%			
Ethanol plant		0.69		72.3	44%	56%	56%	-0.13	-14.0	57%	-0.44	-(20.4)	-20.4
Transport to depot		0.02		1.1	100%	100%	100%			100%			
Refuelling station		0.01		0.4	100%	100%	100%			100%			
Total		**1.01**	**(105.2)**	**108.5**									
Yield	GJ/ha*yr^{-1}			28									
Primary fossil energy	MJ_p/MJ_f				**0.46**	**0.58**	**0.57**			**0.51**			**0.58**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f				**49.0**	**61.8**	**60.9**			**54.7**			**84.8**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f				**47.6**	**60.0**	**59.1**						**88.1**

Table A.1a (*Continued*)

	Gross energy requirement and GHG emissions			Allocation (%)			EU approach			System expansion	
				Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits	
Maize Ethanol (EU default (Romania)) CHP NG											
Location: EU default (Romania), N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.29	25.4	44%	29%	50%			57%		
N2O emissions (IPCC) DNDC			(5.4) 8.7	44%	29%	50%			57%		
Road transport, 50 km		0.01	0.5	44%	29%	50%			57%		
Ethanol plant		1.02	58.9	44%	29%	50%	-0.55	-31.6	57%	-1.05	-(48.0) -48.0
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**1.34**	**(91.8) 95.0**								
Yield	GJ/ha*yr^{-1}		28								
Primary fossil energy	MJ_p/MJ_f			**0.61**	**0.41**	**0.68**			**0.46**		**0.29**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**43.1**	**29.1**	**47.9**			**37.0**		**43.8**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f			**41.6**	**28.1**	**46.3**					**47.0**
Maize Ethanol (EU15) Natural gas boiler											
Location: EU15, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.28	26.3	44%	73%	57%			57%		
N2O emissions (IPCC) Smeets			(8.4) 38.4	44%	73%	57%			57%		
Road transport, 50 km		0.01	0.5	44%	73%	57%			57%		
Ethanol plant		0.79	43.3	44%	73%	57%	0.00	0.0	57%	-0.30	-(14.1) -19.6
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**1.10**	**(80.0) 110.1**								
Yield	GJ/ha*yr^{-1}		74								
Primary fossil energy	MJ_p/MJ_f			**0.50**	**0.81**	**0.64**			**0.64**		**0.80**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**49.7**	**81.2**	**63.7**			**63.7**		**66.0**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**36.4**	**59.1**	**46.5**					**90.5**
Maize Ethanol (East Europe) Natural gas boiler											
Location: East Europe, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.21	16.2	44%	73%	57%			57%		
N2O emissions (IPCC) Smeets			(4.6) 58.7	44%	73%	57%			57%		
Road transport, 50 km		0.01	0.5	44%	73%	57%			57%		
Ethanol plant		0.79	43.3	44%	73%	57%	0.00	0.0	57%	-0.30	-(14.1) -19.6
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**1.03**	**(66.2) 120.2**								
Yield	GJ/ha*yr^{-1}		21								
Primary fossil energy	MJ_p/MJ_f			**0.47**	**0.76**	**0.60**			**0.60**		**0.73**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**54.3**	**88.6**	**69.5**			**69.5**		**52.1**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**30.3**	**49.0**	**38.6**					**###**
Maize Ethanol (US) Natural gas boiler											
Location: US, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.29	26.4	44%	73%	57%			57%		
N2O emissions (IPCC) Smeets			(7.6) 30.7	44%	73%	57%			57%		
Road transport, 50 km		0.01	0.5	44%	73%	57%			57%		
Ethanol plant		0.79	43.3	44%	73%	57%	0.00	0.0	57%	-0.30	-(14.1) -19.6
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**1.11**	**(79.3) 102.4**								
Yield	GJ/ha*yr^{-1}		70								
Primary fossil energy	MJ_p/MJ_f			**0.51**	**0.82**	**0.64**			**0.64**		**0.81**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**46.3**	**75.5**	**59.3**			**59.3**		**65.2**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**36.1**	**58.6**	**46.1**					**82.8**

Table A.1b
Results: ethanol from wheat.

	Gross energy requirement and GHG emissions			Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Wheat Ethanol (EU default (EU)) Natural gas boiler											
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.27	25.9	49%	77%	62%			62%		
N2O emissions (IPCC) DNDC			(7.9) 13.1	49%	77%	62%			62%		
Handling and storage of wheat		0.00	0.1	49%	77%	62%			62%		
Road transport, 50 km		0.01	0.5	49%	77%	62%			62%		
Ethanol plant		0.63	34.1	49%	77%	62%	0.00	0.0	62%	-0.25	-(12.1) -12.1
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.93 (70.1)**	**75.3**								
Yield	$GJ/ha*yr^{-1}$		41								
Primary fossil energy	MJ_p/MJ_f			0.47	0.72	0.59			0.59		0.68
Net GHG emiss. (IPCC)	g. $CO2\text{-eq}/MJ_f$			37.9	58.4	47.3			47.3		58.1
Net GHG emiss. (DNDC)	g. $CO2\text{-eq}/MJ_f$			35.4	54.4	44.1					63.2
Yield	GJ/ha*yr-1		41.03								
Allocation	%			49%	77%	62%			62%		
Land use change related emissions											
Pasture (CE)	Mg. CO2-eq/ha		167								
Set aside (CE)	Mg. CO2-eq/ha		46								
Allocation period:	Years		20								
Pasture (CE)	g. CO2/MJf		203	100	156	126					-523
Set aside (CE)	g. CO2/MJf		56	28	43	35					-27
Net GHG emissions (DNDC)	g. CO2-eq/MJf										
Pasture (CE)				138	215	173					-244
Set aside (CE)				65	101	82					104
Wheat Ethanol (EU default (EU)) DDGS for fuel (biogas)											
Location: , N2O model: , main references:											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.27	25.9	94%	100%	89%			89%		
N2O emissions (IPCC) DNDC			(7.9) 13.1	94%	100%	89%			89%		
Handling and storage of wheat		0.00	0.1	94%	100%	89%			89%		
Road transport, 50 km		0.01	0.5	94%	100%	89%			89%		
Ethanol plant		0.05	2.3	94%	100%	89%	0.00	0.0	89%	-0.12	-(15.2) -15.2
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.36 (38.3)**	**43.5**								
Yield	$GJ/ha*yr^{-1}$		41								
Primary fossil energy	MJ_p/MJ_f			**0.34**	**0.36**	**0.32**			**0.32**		**0.23**
Net GHG emiss. (IPCC)	g. $CO2\text{-eq}/MJ_f$			**40.9**	**43.5**	**38.9**			**38.9**		**23.1**
Net GHG emiss. (DNDC)	g. $CO2\text{-eq}/MJ_f$			**36.0**	**38.3**	**34.3**					**28.3**
Yield	GJ/ha*yr-1		41.03								
Allocation	%			94%	100%	89%			89%		
Land use change related emissions											
Pasture (CE)	Mg. CO2-eq/ha		167								
Set aside (CE)	Mg. CO2-eq/ha		46								
Allocation period:	Years		20								
Pasture (CE)	g. CO2/MJf		203	190	203	181					0
Set aside (CE)	g. CO2/MJf		56	52	56	50					0
Net GHG emissions (DNDC)	g. CO2-eq/MJf										
Pasture (CE)				231	247	220					247
Set aside (CE)				93	99	89					99
Wheat Ethanol (EU default (EU)) CHP NG											
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.27	25.9	49%	37%	56%			62%		
N2O emissions (IPCC) DNDC			(7.9) 13.1	49%	37%	56%			62%		
Handling and storage of wheat		0.00	0.1	49%	37%	56%			62%		
Road transport, 50 km		0.01	0.5	49%	37%	56%			62%		
Ethanol plant		0.76	44.0	49%	37%	56%	-0.38	-22.0	62%	-0.79	-(36.1) -36.1
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**1.06 (80.0)**	**85.2**								
Yield	$GJ/ha*yr^{-1}$		41								
Primary fossil energy	MJ_p/MJ_f			**0.54**	**0.41**	**0.60**			**0.43**		**0.28**
Net GHG emiss. (IPCC)	g. $CO2\text{-eq}/MJ_f$			**42.8**	**32.4**	**48.0**			**39.8**		**43.8**
Net GHG emiss. (DNDC)	g. $CO2\text{-eq}/MJ_f$			**40.3**	**30.5**	**45.2**					**49.0**

Table A.1b (*Continued*)

	Gross energy requirement and GHG emissions		Allocation (%)			EU approach			System expansion		
			Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits		
Wheat Ethanol (EU default (EU)) CHP lignite											
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008											
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.27	25.9	49%	67%	61%			62%			
N2O emissions (IPCC) DNDC		(7.9) 13.1	49%	67%	61%			62%			
Handling and storage of wheat	0.00	0.1	49%	67%	61%			62%			
Road transport, 50 km	0.01	0.5	49%	67%	61%			62%			
Ethanol plant	0.52	54.0	49%	67%	61%	-0.07	-6.9	62%	-0.33	-(15.5)	-15.5
Transport to depot	0.02	1.1	100%	100%	100%			100%			
Refuelling station	0.01	0.4	100%	100%	100%			100%			
Total	**0.82(90.0)**	**95.2**									
Yield	GJ/ha*yr^{-1}	41									
Primary fossil energy	MJ_p/MJ_f		**0.42**	**0.56**	**0.51**			**0.48**			**0.49**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f		**47.8**	**64.0**	**58.7**			**55.4**			**74.5**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f		**45.2**	**60.5**	**55.5**						**79.7**
Wheat Ethanol (EU default (EU)) CHP straw											
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008											
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.30	27.4	49%	53%	59%			62%			
N2O emissions (IPCC) DNDC		(7.9) 13.1	49%	53%	59%			62%			
Handling and storage of wheat	0.00	0.1	49%	53%	59%			62%			
Road transport, 50 km	0.01	0.5	49%	53%	59%			62%			
Ethanol plant	0.00	0.0	49%	53%	59%	0.00	-0.3	62%	-0.47	-(22.0)	-22.0
Transport to depot	0.02	1.1	100%	100%	100%			100%			
Refuelling station	0.01	0.4	100%	100%	100%			100%			
Total	**0.33(37.5)**	**42.7**									
Yield	GJ/ha*yr^{-1}	41									
Primary fossil energy	MJ_p/MJ_f		**0.17**	**0.19**	**0.20**			**0.21**			**-0.15**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f		**21.8**	**23.4**	**25.9**			**26.9**			**15.5**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f		**19.3**	**20.6**	**22.8**						**20.6**
Wheat Ethanol (EU15) Natural gas boiler											
Location: EU15, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.26	24.1	49%	77%	62%			62%			
N2O emissions (IPCC) Smeets		(10.1) 32.2	49%	77%	62%			62%			
Handling and storage of wheat	0.00	0.1	49%	77%	62%			62%			
Road transport, 50 km	0.01	0.5	49%	77%	62%			62%			
Ethanol plant	0.63	34.1	49%	77%	62%	0.00	0.0	62%	-0.27	-(12.7)	-17.7
Transport to depot	0.02	1.1	100%	100%	100%			100%			
Refuelling station	0.01	0.4	100%	100%	100%			100%			
Total	**0.92(70.5)**	**92.6**									
Yield	GJ/ha*yr^{-1}	51									
Primary fossil energy	MJ_p/MJ_f		**0.47**	**0.72**	**0.58**			**0.58**			**0.66**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f		**46.5**	**71.7**	**58.0**			**58.0**			**57.8**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f		**35.6**	**54.7**	**44.3**						**75.0**
Wheat Ethanol (East Europe) Natural gas boiler											
Location: East Europe, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.19	14.6	49%	77%	62%			62%			
N2O emissions (IPCC) Smeets		(4.8) 52.9	49%	77%	62%			62%			
Handling and storage of wheat	0.00	0.1	49%	77%	62%			62%			
Road transport, 50 km	0.01	0.5	49%	77%	62%			62%			
Ethanol plant	0.63	34.1	49%	77%	62%	0.00	0.0	62%	-0.27	-(12.7)	-17.7
Transport to depot	0.02	1.1	100%	100%	100%			100%			
Refuelling station	0.01	0.4	100%	100%	100%			100%			
Total	**0.85(55.7)**	**103.8**									
Yield	GJ/ha*yr^{-1}	15									
Primary fossil energy	MJ_p/MJ_f		**0.43**	**0.66**	**0.54**			**0.54**			**0.59**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f		**52.0**	**80.3**	**64.9**			**64.9**			**43.0**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f		**28.3**	**43.3**	**35.1**						**86.1**

Table A.1c
Results: ethanol from sugar beet.

		Gross energy requirement and GHG emissions		Allocation (%)			EU approach			System expansion	
				Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits	
Sugar beet Ethanol (EU default) Conversion of sugar beet to ethanol (sugar beet pulp used as animal fodder, evaporation drying, no credit for biogas) Location: EU default, N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.11	9.8	60%	99%	71%			72%		
N2O emissions (IPCC) DNDC			(2.3) 6.4	60%	99%	71%			72%		
Road transport, 30 km		0.02	1.2	60%	99%	71%			72%		
Ethanol plant		0.46	25.4	60%	99%	71%	0.00	0.0	72%	-0.05	-(5.8) -6.5
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total (gross)		**0.62**	**(40.2) 44.3**								
Yield	GJ/ha*yr^{-1}		153								
Primary fossil energy	MJ_p/MJ_f			**0.38**	**0.61**	**0.45**			**0.45**		**0.57**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**27.0**	**43.9**	**32.0**			**32.5**		**34.5**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f			**24.6**	**39.9**	**29.1**					**37.8**
Sugar beet Ethanol (EU default) Conversion of sugar beet to ethanol (slop to biogas, sugar beet pulp used as animal fodder, evaporation drying) Location: EU default, N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.11	9.8	60%	99%	72%			72%		
N2O emissions (IPCC) DNDC			(2.3) 6.4	60%	99%	72%			72%		
Road transport, 30 km		0.02	1.2	60%	99%	72%			72%		
Ethanol plant		0.25	12.9	60%	99%	72%	0.00	0.0	72%	-0.05	-(5.8) -6.5
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.40**	**(27.8) 31.8**								
Yield	GJ/ha*yr^{-1}		153								
Primary fossil energy	MJ_p/MJ_f			**0.25**	**0.40**	**0.30**			**0.30**		**0.35**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**19.6**	**31.6**	**23.5**			**23.5**		**22.0**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f			**17.1**	**27.5**	**20.5**					**25.4**
Sugar beet Ethanol (EU default) Conversion of sugar beet to ethanol (slop to biogas, sugar beet pulp combusted, evaporation drying) Location: EU default, N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.11	9.8	100%	100%	71%			100%		
N2O emissions (IPCC) DNDC			(2.3) 6.4	100%	100%	71%			100%		
Road transport, 30 km		0.02	1.2	100%	100%	71%			100%		
Ethanol plant		0.00	0.0	100%	100%	71%	0.00	-0.1	100%	-0.12	-(5.2) -5.2
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.15**	**(14.8) 18.9**								
Yield	GJ/ha*yr^{-1}		153								
Primary fossil energy	MJ_p/MJ_f			**0.15**	**0.15**	**0.12**			**0.15**		**0.04**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**18.9**	**18.9**	**13.9**			**18.8**		**9.6**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f			**14.8**	**14.8**	**11.0**					**13.7**
Sugar beet Ethanol (EU15) Conversion of sugar beet to ethanol (sugar beet pulp used as animal fodder, evaporation drying, no credit for biogas) Location: EU15, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.13	11.4	60%	99%	100%			72%		
N2O emissions (IPCC) Smeets			(5.3) 22.6	60%	99%	100%			72%		
Road transport, 30 km		0.02	1.2	60%	99%	100%			72%		
Ethanol plant		0.46	25.4	60%	99%	100%	0.00	0.0	72%	-0.06	-(6.7) -10.9
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.63**	**(44.9) 62.1**								
Yield	GJ/ha*yr^{-1}		127								
Primary fossil energy	MJ_p/MJ_f			**0.39**	**0.63**	**0.63**			**0.46**		**0.57**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**37.6**	**61.6**	**62.1**			**45.4**		**38.2**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**27.3**	**44.5**	**44.9**					**51.2**
Sugar beet Ethanol (East Europe) Conversion of sugar beet to ethanol (sugar beet pulp used as animal fodder, evaporation drying, no credit for biogas) Location: East Europe, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.09	6.9	60%	99%	72%			72%		
N2O emissions (IPCC) Smeets			(2.2) 31.8	60%	99%	72%			72%		
Road transport, 30 km		0.02	1.2	60%	99%	72%			72%		
Ethanol plant		0.46	25.4	60%	99%	72%	0.00	0.0	72%	-0.03	-(3.3) -9.9
Transport to depot		0.02	1.1	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.59**	**(37.2) 66.8**								
Yield	GJ/ha*yr^{-1}		38								
Primary fossil energy	MJ_p/MJ_f			**0.36**	**0.59**	**0.43**			**0.43**		**0.56**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**40.4**	**66.2**	**48.8**			**48.8**		**33.8**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**22.8**	**36.9**	**27.4**					**56.9**

Table A.1d
Results: ethanol from maize.

	Gross energy requirement and GHG emissions				Allocation (%)			EU approach			System expansion		
					Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits		
Sugar cane Ethanol (EU default (Brazil), but updated for Macedo 2008 (Macedo 2004 in EU)) Conversion of sugar cane to ethanol (bagasse export, default case)													
Location: Brazil, N2O model: IPCC, main references: Macedo 2008													
		MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.10		8.4	86%	99%	92%			92%			
N2O emissions (IPCC) IPCC			(6.7)	6.7	86%	99%	92%			92%			
Road transport, 50 km		0.02		1.4	86%	99%	92%			92%			
Ethanol plant		0.05		2.2	86%	99%	92%	0.00	0.0	92%	0.00	(0.0)	0.0
Transport to depot (EU)		0.08		5.9	100%	100%	100%			100%			
Refuelling station		0.01		0.4	100%	100%	100%			100%			
Total		**0.26**	**(25.1)**	**25.1**									
Yield	GJ/ha*yr^{-1}			130									
Primary fossil energy	MJ_p/MJ_f				**0.23**	**0.26**	**0.24**			**0.24**			**0.26**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**22.4**	**24.9**	**23.5**			**23.5**			**25.1**
Sugar cane, worst, present													
Location: Brazil, N2O model: IPCC, main references: Macedo et al. 2004													
		MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.12		6.9	100%	100%	100%						
N2O emissions (IPCC) IPCC		0.00	(1.7)	1.7	100%	100%	100%						
Road transport, 50 km		0.01		0.6	100%	100%	100%						
Ethanol plant		0.00		0.0	100%	100%	100%				0.00	(0.0)	0.0
Transport to depot (EU)		0.07		5.2	100%	100%	100%						
Refuelling station		0.01		0.5	100%	100%	100%						
Total		**0.32**	**(18.2)**	**18.2**									
Yield	GJ/ha*yr^{-1}			103									
Primary fossil energy	MJ_p/MJ_f				**0.32**	**0.32**	**0.32**			**0.00**			**0.32**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**18.2**	**18.2**	**18.2**			**0.0**			**18.2**
Land use change related emissions													
Grassland	Mg. CO2-eq/ha			30									
Woody Cerrado/Cerradão	Mg. CO2-eq/ha			165									
Allocation period:	Years			20									
Grassland	g. CO2/MJf			14	14	14	14						
Woody Cerrado/Cerradão	g. CO2/MJf			80	80	80	80						
Net GHG emissions (IPCC)													
Grassland	g. CO2/MJf				33	33	33						33
Woody Cerrado/Cerradão	g. CO2/MJf				98	98	98						98
Sugar cane, default, present													
Location: Brazil, N2O model: IPCC, main references: Macedo et al. 2004, Smeets et al. 2008													
		MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.10		5.9	100%	98%	94%						
N2O emissions (IPCC) IPCC		0.00	(1.3)	1.3	100%	98%	94%						
Road transport, 50 km		0.01		0.6	100%	98%	94%						
Ethanol plant		0.00		0.0	100%	98%	94%				-0.08	-(5.8)	-5.8
Transport to depot (EU)		0.07		5.2	100%	100%	100%						
Refuelling station		0.01		0.5	100%	100%	100%						
Total		**0.31**	**(17.3)**	**17.3**									
Yield	GJ/ha*yr^{-1}			129									
Primary fossil energy	MJ_p/MJ_f				**0.31**	**0.30**	**0.30**						**0.23**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**17.3**	**17.0**	**16.6**						**11.4**
Land use change related emissions													
Grassland	Mg. CO2-eq/ha			30									
Woody Cerrado/Cerradão	Mg. CO2-eq/ha			165									
Allocation period:	Years			20									
Grassland	g. CO2/MJf			11	11	11	11						
Woody Cerrado/Cerradão	g. CO2/MJf			63.9	64	62	60						
Net GHG emissions (IPCC)													
Grassland	g. CO2/MJf				29	28	27						23
Woody Cerrado/Cerradão	g. CO2/MJf				81	79	77						75

Table A.1d (*Continued*)

		Gross energy requirement and GHG emissions			Allocation (%)			EU approach			System expansion		
					Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits		
Sugar cane, best, present													
Location: Brazil, N2O model: IPCC, main references: Macedo et al. 2004, Smeets et al. 2008													
		MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.09		5.6	100%	95%	98%						
N2O emissions (IPCC) IPCC		0.00	(1.3)	1.3	100%	95%	98%						
Road transport, 50 km		0.01		0.5	100%	95%	98%						
Ethanol plant		0.00		0.0	100%	95%	98%				-0.04	-(2.2)	-2.2
Transport to depot (EU)		0.02		1.5	100%	100%	100%						
Refuelling station		0.01		0.5	100%	100%	100%						
Total		**0.25**	**(13.0)**	**13.0**									
Yield	GJ/ha*yr^{-1}			134									
Primary fossil energy	MJ_p/MJ_f				**0.25**	**0.24**	**0.25**						**0.21**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**13.0**	**12.4**	**12.8**						**10.8**
Land use change related emissions													
Grassland	Mg. CO2-eq/ha			30									
Woody Cerrado/Cerradão	Mg. CO2-eq/ha			165									
Allocation period:	Years			20									
Grassland	g. CO2/MJf			11	11	10	11						
Woody Cerrado/Cerradão	g. CO2/MJf			62	62	59	61						
Net GHG emissions (IPCC)													
Grassland	g. CO2/MJf				24	23	24						22
Woody Cerrado/Cerradão	g. CO2/MJf				75	71	73						73
Sugar cane, worst, future													
Location: Brazil, N2O model: IPCC, main references: Macedo et al. 2004, Smeets et al. 2008													
		MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.07		4.9	100%	77%	91%						
N2O emissions (IPCC) IPCC		0.00	(1.3)	1.3	100%	77%	91%						
Road transport, 50 km		0.01		0.5	100%	77%	91%						
Ethanol plant		0.00		0.0	100%	77%	91%				-0.18	-(9.7)	-9.7
Transport to depot (EU)		0.02		1.5	100%	100%	100%						
Refuelling station		0.01		0.5	100%	100%	100%						
Total		**0.23**	**(12.3)**	**12.3**									
Yield	GJ/ha*yr^{-1}			196									
Primary fossil energy	MJ_p/MJ_f				**0.23**	**0.19**	**0.21**						**0.05**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**12.3**	**10.0**	**11.4**						**2.6**
Land use change related emissions													
Grassland	Mg. CO2-eq/ha			30									
Woody Cerrado/Cerradão	Mg. CO2-eq/ha			165									
Allocation period:	Years			20									
Grassland	g. CO2/MJf			8	8	6	7						
Woody Cerrado/Cerradão	g. CO2/MJf			42	42	33	38						
Net GHG emissions (IPCC)													
Grassland	g. CO2/MJf				20	16	18						10
Woody Cerrado/Cerradão	g. CO2/MJf				55	43	50						45
Sugar cane, default, future													
Location: Brazil, N2O model: IPCC, main references: Macedo et al. 2004, Smeets et al. 2008													
		MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.08		5.6	100%	63%	83%						
N2O emissions (IPCC) IPCC		0.00	(1.3)	1.3	100%	63%	83%						
Road transport, 50 km		0.01		0.5	100%	63%	83%						
Ethanol plant		0.00		0.0	100%	63%	83%				-0.35	-(19.1)	-19.1
Transport to depot (EU)		0.02		1.5	100%	100%	100%						
Refuelling station		0.01		0.5	100%	100%	100%						
Total		**0.24**	**(11.6)**	**11.6**									
Yield	GJ/ha*yr^{-1}			196									
Primary fossil energy	MJ_p/MJ_f				**0.24**	**0.16**	**0.21**			**0.00**			**-0.11**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**11.6**	**8.1**	**10.0**						**-7.5**
Land use change related emissions													
Grassland	Mg. CO2-eq/ha			30									
Woody Cerrado/Cerradão	Mg. CO2-eq/ha			165									
Allocation period:	Years			20									
Grassland	g. CO2/MJf			8	8	5	6						
Woody Cerrado/Cerradão	g. CO2/MJf			42	42	27	35						
Net GHG emissions (IPCC)													
Grassland	g. CO2/MJf				19	13	16						0
Woody Cerrado/Cerradão	g. CO2/MJf				54	35	45						35

Table A.1d (*Continued*)

		Gross energy requirement and GHG emissions		Allocation (%)			EU approach			System expansion	
				Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits	
Sugar cane, best, future											
Location: Brazil, N2O model: IPCC, main references: Macedo et al. 2004, Smeets et al. 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.08	5.6	100%	39%	64%					
N2O emissions (IPCC)		0.00	(1.3) 1.3	100%	39%	64%					
Road transport, 50 km		0.01	0.5	100%	39%	64%					
Ethanol plant		0.00	0.0	100%	39%	64%				-0.96	-(52.1) -52.1
Transport to depot (EU)		0.02	1.5	100%	100%	100%					
Refuelling station		0.01	0.5	100%	100%	100%					
Total		**0.24**	**(11.6)11.6**								
Yield	GJ/ha*yr^{-1}		196								
Primary fossil energy	MJ_p/MJ_f			**0.24**	**0.11**	**0.17**			**0.00**		**-0.72**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**11.6**	**5.8**	**8.2**					**-40.4**
Land use change related emissions											
Grassland	Mg. CO2-eq/ha		30								
Woody Cerrado/Cerradão	Mg. CO2-eq/ha		165								
Allocation period:	Years		20								
Grassland	g. CO2/MJf		8	8	3	5					
Woody Cerrado/Cerradão	g. CO2/MJf		42	42	16	27					
Net GHG emissions (IPCC)											
Grassland	g. CO2/MJf			19	9	13					-33
Woody Cerrado/Cerradão	g. CO2/MJf			54	22	35					2

Table A.1e
Results: ethanol from sweet sorghum.

		Gross energy requirement and GHG emissions		Allocation (%)			EU approach			System expansion	
				Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits	
Sorghum Ethanol (China) Excess bagasse for fuel (heat)											
Location: US, N2O model: IPCC, main references: Bennet et al. 2009, JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.10	10.1	76%	99%	78%			85%		
N2O emissions (IPCC) IPCC			(15.5) 15.5	76%	99%	78%			85%		
Road transport, 50 km		0.02	1.2	76%	99%	78%			85%		
Ethanol plant		0.00	0.0	76%	99%	78%	-0.20	-11.7	85%	-0.29	-(12.9) -12.9
Transport to depot		0.01	0.6	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.14**	**(27.9) 27.9**								
Yield	GJ/ha*yr^{-1}		92								
Primary fossil energy	MJ_p/MJ_f			**0.11**	**0.14**	**0.11**			**-0.05**		**-0.15**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**21.5**	**27.5**	**22.1**			**13.9**		**15.1**

Table A. 2a
Results: FAME from palm oil.

	Gross energy requirement and GHG emissions		Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Palm fruit FAME (South East Asia) Including emissions POME										
Location: EU default (South East Asia), N2O model: IPCC, main references: JEC 2008										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.11	9.5	82%	92%	91%			91%		
N2O emissions (IPCC) IPCC		(7.2) 7.2	82%	92%	91%			91%		
FFB storage	0.00	0.0	82%	92%	91%			91%		
Road transport, 50 km	0.00	0.2	82%	92%	91%			91%		
Storage	0.00	0.9	82%	92%	91%			91%		
Oil mill	0.00	24.7	82%	92%	91%	0.00	0.0	91%	-0.02	-(1.3) -1.3
Transport to EU	0.04	2.9	82%	92%	91%			91%		
Oil refining	0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification	0.13	9.3	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.32**	**(56.7) 56.7**								
Yield	GJ/ha*yr^{-1}	148								
Primary fossil energy	MJ_p/MJ_f		**0.28**	**0.29**	**0.30**			**0.30**		**0.24**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**47.7**	**52.5**	**52.4**			**52.4**		**49.2**
Land use change related emissions (t CO_2/ha)										
Degraded land (Wicke et al. 2008)		-90	-74	-83	-82					
Logged-over forest (Wicke et al. 2008)		433	356	401	396					
Natural rain forest (Wicke et al. 2008)		748	615	691	684					
Peatland natural rain forest (Wicke et al. 2008)		1580	1299	1461	1445					
Lowland Tropical rainforest (Fargione et al. 2008)		697	573	645	638					
Allocation period:	Years	20								
Net GHG emissions (IPCC) (g. $CO_{2\text{-}eq}/MJ_f$)										
Degraded land (Wicke et al. 2008)			23	24	25					
Logged-over forest (Wicke et al. 2008)			168	188	186					
Natural rain forest (Wicke et al. 2008)			256	286	284					
Peatland natural rain forest (Wicke et al. 2008)			487	546	541					
Lowland Tropical rainforest (Fargione et al. 2008)			242	271	268					
Palm fruit FAME (South East Asia) Esterification (the glycerol converted to biogas which is converted to steam)										
Location: EU default (South East Asia), N2O model: IPCC, main references: JEC 2008										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.11	9.5	91%	100%	96%			96%		
N2O emissions (IPCC) IPCC		(7.2) 7.2	91%	100%	96%			96%		
FFB storage	0.00	0.0	91%	100%	96%			96%		
Road transport, 50 km	0.00	0.2	91%	100%	96%			96%		
Storage	0.00	4.8	91%	100%	96%			96%		
Oil mill	0.00	24.7	91%	100%	96%	0.00	0.0	96%	-0.02	-(1.3) -1.3
Transport to EU	0.04	2.9	91%	100%	96%			96%		
Oil refining	0.01	0.7	100%	100%	100%	0.00	0.0	100%	0.00	(0.0) 0.0
Transesterification	0.09	6.8	100%	100%	100%	0.00	0.0	100%	0.00	(0.0) 0.0
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.27**	**(58.2) 58.2**								
Yield	GJ/ha*yr^{-1}	148								
Primary fossil energy	MJ_p/MJ_f		**0.26**	**0.27**	**0.27**			**0.27**		**0.26**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**53.7**	**58.2**	**56.0**			**56.0**		**56.8**
Palm fruit FAME (South East Asia) Including emissions POME										
Location: South East Asia, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.08	7.3	81%	92%	91%			91%		
N2O emissions (IPCC) Smeets		(6.4) 5.1	81%	92%	91%			91%		
FFB storage	0.00	0.0	81%	92%	91%			91%		
Road transport, 50 km	0.00	0.2	81%	92%	91%			91%		
Storage	0.00	8.4	81%	92%	91%			91%		
Oil mill	0.00	26.1	81%	92%	91%	0.00	0.0	91%	-0.02	-(1.6) -1.6
Transport to EU	0.04	3.1	81%	92%	91%			91%		
Oil refining	0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification	0.13	9.3	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.29**	**(62.8) 61.4**								
Yield	GJ/ha*yr^{-1}	143								
Primary fossil energy	MJ_p/MJ_f		**0.26**	**0.27**	**0.28**			**0.28**		**0.22**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f		**51.1**	**56.9**	**56.5**			**56.5**		**55.1**

Table A. 2b
Results: FAME from soy.

	Gross energy requirement and GHG emissions		Allocation (%)			EU approach			System expansion	
			Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits	
Soy beans FAME (EU default (Brazil)) Esterification										
Location: EU default (Brazil) , N2O model: IPCC, main references: JEC 2008										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.29	21.5	19%	39%	33%			33%		
N2O emissions (IPCC) IPCC		(37.3) 37.3	19%	39%	33%			33%		
Road transport, 700 km	0.12	9.1	19%	39%	33%			33%		
Oil mill	0.34	24.7	19%	39%	33%	0.00	0.0	33%	-0.27	-(32.1) -36.0
Transport to EU	0.30	16.0	19%	39%	33%			33%		
Oil refining	0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification	0.13	9.3	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**1.22**	**(119.8) 119.8**								
Yield	$GJ/ha{*}yr^{-1}$	18								
Primary fossil energy	MJ_p/MJ_f		**0.35**	**0.56**	**0.50**			**0.50**		**0.88**
Net GHG emissions (IPCC)	g. $CO2\text{-}eq/MJ_f$		**31.3**	**52.4**	**46.1**			**46.1**		**81.6**
Soy beans FAME (EU default (Brazil)) Glycerine for fuel (process heat)										
Location: EU default (Brazil) , N2O model: IPCC, main references: JEC 2008										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.29	21.5	21%	42%	34%			34%		
N2O emissions (IPCC) IPCC		(37.3) 37.3	21%	42%	34%			34%		
Road transport, 700 km	0.12	9.1	21%	42%	34%			34%		
Oil mill	0.35	25.2	21%	42%	34%	0.00	0.0	34%	-0.27	-(32.1) -36.0
Transport to EU	0.30	16.0	21%	42%	34%			34%		
Oil refining	0.01	0.7	100%	100%	100%	0.00	0.0	100%	0.00	(0.0) 0.0
Transesterification	0.12	8.9	100%	100%	100%	0.00	0.0	100%	0.00	(0.0) 0.0
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**1.22**	**(120.0) 120.0**								
Yield	$GJ/ha{*}yr^{-1}$	18								
Primary fossil energy	MJ_p/MJ_f		**0.38**	**0.60**	**0.52**			**0.52**		**0.95**
Net GHG emissions (IPCC)	g. $CO2\text{-}eq/MJ_f$		**34.2**	**56.5**	**48.0**			**48.0**		**88.0**
Soy beans FAME (Brazil) Esterification										
Location: Brazil, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.30	22.6	19%	39%	33%			33%		
N2O emissions (IPCC) Smeets		(47.8) 90.3	19%	39%	33%			33%		
Road transport, 700 km	0.12	9.1	19%	39%	33%			33%		
Oil mill	0.35	25.2	19%	39%	33%	0.00	0.0	33%	-0.27	-(37.1) -60.7
Transport to EU	0.30	16.0	19%	39%	33%			33%		
Oil refining	0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification	0.13	9.3	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**1.24**	**(132.0) 174.4**								
Yield	$GJ/ha{*}yr^{-1}$	15								
Primary fossil energy	MJ_p/MJ_f		**0.36**	**0.57**	**0.51**			**0.51**		**0.91**
Net GHG emiss. (IPCC)	g. $CO2\text{-}eq/MJ_f$		**41.9**	**73.6**	**63.9**			**63.9**		**88.7**
Net GHG emiss. (Smeets)	g. $CO2\text{-}eq/MJ_f$		**33.7**	**57.2**	**50.1**					**107.6**
Soy beans FAME (US) Esterification										
Location: US, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.36	28.3	19%	39%	33%			33%		
N2O emissions (IPCC) Smeets		(47.5) 78.8	19%	39%	33%			33%		
Road transport, 700 km	0.12	9.1	19%	39%	33%			33%		
Oil mill	0.35	25.2	19%	39%	33%	0.00	0.0	33%	-0.27	-(37.1) -60.7
Transport to EU	0.30	16.0	19%	39%	33%			33%		
Oil refining	0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification	0.13	9.3	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot	0.01	0.8	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**1.29**	**(137.3) 168.6**								
Yield	$GJ/ha{*}yr^{-1}$	16								
Primary fossil energy	MJ_p/MJ_f		**0.37**	**0.59**	**0.52**			**0.52**		**0.97**
Net GHG emiss. (IPCC)	g. $CO2\text{-}eq/MJ_f$		**40.7**	**71.3**	**62.0**			**62.0**		**94.0**
Net GHG emiss. (Smeets)	g. $CO2\text{-}eq/MJ_f$		**34.7**	**59.2**	**51.8**					**101.8**

Table A. 2c
Results: FAME from rapeseed.

	Gross energy requirement and GHG emissions			Allocation (%)			EU approach			System expansion		
				Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits		
Rapeseed FAME (EU default (EU)) Rape meal and glycerine by-products												
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008												
		MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	
Cultivation		0.27	27.9	39%	72%	59%			59%			
N2O emissions (IPCC) DNDC		(15.2)	21.8	39%	72%	59%			59%			
Drying		0.00	0.7	39%	72%	59%			59%			
Road transport, 50 km		0.00	0.3	39%	72%	59%			59%			
Oil mill		0.08	4.6	39%	72%	59%	0.00	0.0	59%	-0.41	-(33.0)	-33.0
Oil refining		0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0)	0.0
Transesterification		0.13	9.4	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2)	-6.2
Transport to depot		0.01	0.8	100%	100%	100%			100%			
Refuelling station		0.01	0.4	100%	100%	100%			100%			
Total		**0.53(60.1)**	**66.7**									
Yield	GJ/ha*yr^{-1}		42									
Primary fossil energy	MJ_p/MJ_f			**0.29**	**0.41**	**0.37**			**0.37**			**0.06**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**31.9**	**50.5**	**43.3**			**43.3**			**20.9**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f			**29.3**	**45.7**	**39.4**						**27.5**
Rapeseed FAME (EU15) Rape meal and glycerine by-products												
Location: EU15, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009												
		MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	
Cultivation		0.32	32.8	39%	72%	59%			59%			
N2O emissions (IPCC) Smeets		(25.8)	69.8	39%	72%	59%			59%			
Drying		0.00	0.7	39%	72%	59%			59%			
Road transport, 50 km		0.00	0.3	39%	72%	59%			59%			
Oil mill		0.08	4.6	39%	72%	59%	0.00	0.0	59%	-0.41	-(35.2)	-33.0
Oil refining		0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0)	0.0
Transesterification		0.13	9.4	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2)	-6.2
Transport to depot		0.01	0.8	100%	100%	100%			100%			
Refuelling station		0.01	0.4	100%	100%	100%			100%			
Total		**0.57(75.5)**	**119.5**									
Yield	GJ/ha*yr^{-1}		41									
Primary fossil energy	MJ_p/MJ_f			**0.31**	**0.45**	**0.40**			**0.40**			**0.10**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**52.5**	**88.6**	**74.3**			**74.3**			**34.1**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**35.3**	**56.9**	**48.5**						**80.3**
Rapeseed FAME (East Europe) Rape meal and glycerine by-products												
Location: East Europe, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009												
		MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	
Cultivation		0.22	19.6	39%	72%	59%			59%			
N2O emissions (IPCC) Smeets		(17.6)	141.8	39%	72%	59%			59%			
Drying		0.00	0.7	39%	72%	59%			59%			
Road transport, 50 km		0.00	0.3	39%	72%	59%			59%			
Oil mill		0.08	4.6	39%	72%	59%	0.00	0.0	59%	-0.41	-(35.2)	-41.5
Oil refining		0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0)	0.0
Transesterification		0.13	9.4	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2)	-6.2
Transport to depot		0.01	0.8	100%	100%	100%			100%			
Refuelling station		0.01	0.4	100%	100%	100%			100%			
Total		**0.47(54.2)**	**178.3**									
Yield	GJ/ha*yr^{-1}		9									
Primary fossil energy	MJ_p/MJ_f			**0.27**	**0.37**	**0.34**			**0.34**			**0.00**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**75.4**	**131.1**	**108.7**			**108.7**			**12.7**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**27.0**	**41.5**	**36.0**						**130.6**

Table A. 2c (*Continued*)

		Gross energy requirement and GHG emissions		Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Rapeseed FAME (Canada) Rape meal and glycerine by-products											
Location: Canada, N2O model: Smeets, main references: JEC 2008, Smeets et al. 2009											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.30	31.2	39%	72%	59%			59%		
N2O emissions (IPCC) Smeets			(19.4) 70.2	39%	72%	59%			59%		
Drying		0.00	0.7	39%	72%	59%			59%		
Road transport, 50 km		0.00	0.3	39%	72%	59%			59%		
Oil mill		0.08	4.6	39%	72%	59%	0.00	0.0	59%	-0.41	-(35.2) -41.5
Oil refining		0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification		0.13	9.4	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transport to depot		0.01	0.8	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.56**	**(67.6) 118.3**								
Yield	GJ/ha*yr^{-1}		20								
Primary fossil energy	MJ_p/MJ_f			**0.30**	**0.44**	**0.39**			**0.39**		**0.14**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**52.0**	**87.8**	**73.6**			**73.6**		**32.4**
Net GHG emiss. (Smeets)	g. CO2-eq/MJ_f			**32.3**	**51.1**	**43.8**					**76.8**
Rapeseed FAME (EU default (EU)) Rape meal and glycerine for fuel (process heat)											
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.27	27.9	83%	92%	77%			85%		
N2O emissions (IPCC) DNDC			(15.2) 21.8	83%	92%	77%			85%		
Drying		0.00	0.7	83%	92%	77%			85%		
Road transport, 50 km		0.00	0.3	83%	92%	77%			85%		
Oil mill		0.00	0.3	83%	92%	77%	-0.01	-0.4	85%	-0.49	-(31.9) -31.9
Oil refining		0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification		0.09	6.9	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot		0.01	0.8	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.40**	**(53.3) 59.9**								
Yield	GJ/ha*yr^{-1}		42								
Primary fossil energy	MJ_p/MJ_f			**0.35**	**0.37**	**0.33**			**0.35**		**-0.14**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**50.6**	**55.5**	**48.0**			**51.8**		**15.2**
Net GHG emiss. (DNDC)	g. CO2-eq/MJ_f			**45.1**	**49.3**	**42.8**					**21.8**
Rapeseed FAME (EU default (EU)) Rape meal and glycerine by-products											
Location: EU default (EU), N2O model: DNDC, main references: JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$
Cultivation		0.21	15.4	39%	72%	59%			59%		
N2O emissions (IPCC) DNDC			(13.7) 18.3	39%	72%	59%			59%		
Drying		0.00	0.6	39%	72%	59%			59%		
Road transport, 50 km		0.00	0.3	39%	72%	59%			59%		
Oil mill		0.08	4.1	39%	72%	59%	0.00	0.0	59%	-0.41	-(33.0) -33.0
Oil refining		0.01	0.6	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification		0.12	9.0	90%	92%	96%	0.00	0.0	96%	-0.06	-(6.2) -6.2
Transport to depot		0.01	0.8	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.45**	**(45.1) 49.7**								
Yield	GJ/ha*yr^{-1}		51								
Primary fossil energy	MJ_p/MJ_f			**0.26**	**0.36**	**0.32**			**0.32**		**-0.02**
Net GHG emissions (DNDC)	g. CO2-eq/MJ_f			**25.1**	**38.2**	**33.2**			**33.2**		**5.9**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**23.3**	**34.8**	**30.5**					**10.5**

Table A. 2d
Results: FAME from jatropha.

		Gross energy requirement and GHG emissions		Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Jatropha FAME (Tanzania) Esterification											
Location: Tanzania, N2O model: IPCC, main references: Croezen 2008/JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation		0.22	21.2	90%	92%	87%			96%		
N2O emissions (IPCC) IPCC			(12.7) 12.7	90%	92%	87%			96%		
Drying		0.00	0.0	90%	92%	87%			96%		
Road transport, 50 km		0.00	0.1	90%	92%	87%			96%		
Oil mill		0.01	0.4	90%	92%	87%	-0.21	-11.9	96%	-0.29	-(13.1) -13.1
Shipping to EU (10,000 km)		0.00	0.8	90%	92%	87%			96%		
Oil refining		0.01	0.7	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transesterification		0.13	9.3	90%	92%	96%	0.00	0.0	96%	0.00	(0.0) 0.0
Transport to depot		0.01	0.8	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.39**	**(46.5) 46.5**								
Yield	$GJ/ha*yr^{-1}$		55								
Primary fossil energy	MJ_p/MJ_f			**0.35**	**0.36**	**0.35**			**0.17**		**0.10**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**42.1**	**43.0**	**41.5**			**33.1**		**33.4**
Jatropha FAME (Tanzania) Esterification (the glycerol converted to biogas which is converted to steam)											
Location: Tanzania, N2O model: IPCC, main references: Croezen 2008/JEC 2008											
		MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation		0.22	21.2	100%	100%	91%			100%		
N2O emissions (IPCC) IPCC			(12.7) 12.7	100%	100%	91%			100%		
Drying		0.00	0.0	100%	100%	91%			100%		
Road transport, 50 km		0.00	0.1	100%	100%	91%			100%		
Oil mill		0.01	0.4	100%	100%	91%	-0.21	-11.9	100%	-0.29	-(13.1) -13.1
Shipping to EU (10,000 km)		0.00	0.8	100%	100%	91%			100%		
Oil refining		0.01	0.7	100%	100%	100%	0.00	0.0	100%	0.00	(0.0) 0.0
Transesterification		0.09	6.8	100%	100%	100%	0.00	0.0	100%	-0.01	-(0.4) -0.4
Transport to depot		0.01	0.8	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.34**	**(44.0) 44.0**								
Yield	$GJ/ha*yr^{-1}$		55								
Primary fossil energy	MJ_p/MJ_f			**0.34**	**0.34**	**0.32**			**0.14**		**0.04**
Net GHG emiss. (IPCC)	g. CO2-eq/MJ_f			**44.0**	**44.0**	**40.8**			**32.0**		**30.5**

Table A. 3a
Results: ethanol from switchgrass.

	Gross energy requirement and GHG emissions		Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Switchgrass Ethanol (EU15) Excluding pelletization										
Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2004										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.10	9.9	100%	95%	95%			100%		
N_2O emissions		(7.1) 7.1	100%	95%	95%			100%		
Storage	0.01	0.6	100%	95%	95%			100%		
Road transport, 100 km	0.02	1.2	100%	95%	95%			100%		
Bulk inland carrier, 400 km	0.02	1.5	100%	95%	95%			100%		
Ethanol+ plant	0.10	3.4	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7) -6.7
Transport to depot	0.02	1.1	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.27**	**(25.1) 25.1**								
Yield	GJ/ha*yr^{-1}	103								
Primary fossil energy	MJ_p/MJ_f		**0.27**	**0.26**	**0.26**			**0.16**		**0.12**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**25.1**	**24.0**	**24.0**			**19.0**		**18.4**
Switchgrass Ethanol (East Europe) Excluding pelletization										
Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2004										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.10	9.9	100%	95%	95%			100%		
N_2O emissions		(7.1) 7.1	100%	95%	95%			100%		
Storage	0.01	0.6	100%	95%	95%			100%		
Road transport, 100 km	0.02	1.2	100%	95%	95%			100%		
Bulk inland carrier, 400 km	0.02	1.5	100%	95%	95%			100%		
Ethanol+ plant	0.00	0.0	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7) -6.7
Transport to depot	0.02	1.1	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.17**	**(21.7) 21.7**								
Yield	GJ/ha*yr^{-1}	103								
Primary fossil energy	MJ_p/MJ_f		**0.17**	**0.16**	**0.16**			**0.06**		**0.02**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**21.7**	**20.7**	**20.7**			**15.6**		**15.0**
Switchgrass Ethanol (EU15) Excluding pelletization										
Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2030										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.07	5.3	100%	95%	95%			100%		
N_2O emissions		(7.1) 7.1	100%	95%	95%			100%		
Storage	0.01	0.6	100%	95%	95%			100%		
Road transport, 100 km	0.02	1.2	100%	95%	95%			100%		
Bulk inland carrier, 400 km	0.02	1.5	100%	95%	95%			100%		
Ethanol+ plant	0.00	0.0	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7) -6.7
Transport to depot	0.02	1.1	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.14**	**(17.2) 17.2**								
Yield	GJ/ha*yr^{-1}	145								
Primary fossil energy	MJ_p/MJ_f		**0.14**	**0.14**	**0.14**			**0.04**		**-0.01**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**17.2**	**16.4**	**16.4**			**11.0**		**10.5**
Switchgrass Ethanol (East Europe) Excluding pelletization										
Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2030										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.07	5.2	100%	95%	95%			100%		
N_2O emissions		(7.1) 7.1	100%	95%	95%			100%		
Storage	0.01	0.6	100%	95%	95%			100%		
Road transport, 100 km	0.02	1.2	100%	95%	95%			100%		
Bulk inland carrier, 400 km	0.02	1.5	100%	95%	95%			100%		
Ethanol+ plant	0.00	0.0	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7) -6.7
Transport to depot	0.02	1.1	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.14**	**(17.0) 17.0**								
Yield	GJ/ha*yr^{-1}	157								
Primary fossil energy	MJ_p/MJ_f		**0.14**	**0.13**	**0.13**			**0.03**		**-0.01**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**17.0**	**16.2**	**16.2**			**10.9**		**10.3**

Table A. 3b
Results: ethanol from miscanthus.

	Gross energy requirement and GHG emissions			Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits		
Miscanthus Ethanol (EU15) Excluding pelletization Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2004												
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$		%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.09		7.5	100%	95%	95%			100%			
N_2O emissions		(3.5)	3.5	100%	95%	95%			100%			
Storage	0.01		0.6	100%	95%	95%			100%			
Road transport, 100 km	0.02		1.2	100%	95%	95%			100%			
Bulk inland carrier, 400 km	0.02		1.5	100%	95%	95%			100%			
Ethanol+ plant	0.10		3.4	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7)	-6.7
Transport to depot	0.01		0.6	100%	100%	100%			100%			
Refuelling station	0.01		0.4	100%	100%	100%			100%			
Total	**0.25**	**(18.7)**	**18.7**									
Yield	$GJ/ha*yr^{-1}$		128									
Primary fossil energy	MJ_p/MJ_f			**0.25**	**0.24**	**0.24**			**0.15**			**0.10**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**18.7**	**17.8**	**17.8**			**12.6**			**12.0**
Miscanthus Ethanol (East Europe) Excluding pelletization Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2004												
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$		%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.08		7.3	100%	95%	95%			100%			
N_2O emissions		(3.5)	3.5	100%	95%	95%			100%			
Storage	0.01		0.6	100%	95%	95%			100%			
Road transport, 100 km	0.02		1.2	100%	95%	95%			100%			
Bulk inland carrier, 400 km	0.02		1.5	100%	95%	95%			100%			
Ethanol+ plant	0.10		3.4	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7)	-6.7
Transport to depot	0.01		0.6	100%	100%	100%			100%			
Refuelling station	0.01		0.4	100%	100%	100%			100%			
Total	**0.25**	**(18.5)**	**18.5**									
Yield	$GJ/ha*yr^{-1}$		136									
Primary fossil energy	MJ_p/MJ_f			**0.25**	**0.24**	**0.24**			**0.14**			**0.10**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**18.5**	**17.6**	**17.6**			**12.4**			**11.8**
Miscanthus Ethanol (EU15) Excluding pelletization Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2030												
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$		%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.06		4.5	100%	95%	95%			100%			
N_2O emissions		(3.5)	3.5	100%	95%	95%			100%			
Storage	0.01		0.6	100%	95%	95%			100%			
Road transport, 100 km	0.02		1.2	100%	95%	95%			100%			
Bulk inland carrier, 400 km	0.02		1.5	100%	95%	95%			100%			
Ethanol+ plant	0.10		3.4	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7)	-6.7
Transport to depot	0.01		0.6	100%	100%	100%			100%			
Refuelling station	0.01		0.4	100%	100%	100%			100%			
Total	**0.23**	**(15.7)**	**15.7**									
Yield	$GJ/ha*yr^{-1}$		181									
Primary fossil energy	MJ_p/MJ_f			**0.23**	**0.22**	**0.22**			**0.12**			**0.08**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**15.7**	**15.0**	**15.0**			**9.6**			**9.0**
Miscanthus Ethanol (East Europe) Excluding pelletization Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2030												
	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$		%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-eq}}/MJ_f$	
Cultivation	0.06		4.3	100%	95%	95%			100%			
N_2O emissions		(3.5)	3.5	100%	95%	95%			100%			
Storage	0.01		0.6	100%	95%	95%			100%			
Road transport, 100 km	0.02		1.2	100%	95%	95%			100%			
Bulk inland carrier, 400 km	0.02		1.5	100%	95%	95%			100%			
Ethanol+ plant	0.10		3.4	100%	95%	95%	-0.11	-6.1	100%	-0.15	-(6.7)	-6.7
Transport to depot	0.01		0.6	100%	100%	100%			100%			
Refuelling station	0.01		0.4	100%	100%	100%			100%			
Total	**0.23**	**(15.5)**	**15.5**									
Yield	$GJ/ha*yr^{-1}$		196									
Primary fossil energy	MJ_p/MJ_f			**0.23**	**0.21**	**0.21**			**0.12**			**0.08**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**15.5**	**14.8**	**14.8**			**9.3**			**8.8**

Table A. 3c
Results: ethanol from eucalyptus.

		Gross energy requirement and GHG emissions			Allocation (%)			EU approach			System expansion		
					Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits		
Eucalyptus Ethanol (Brazil) Ethanol hydrolysis with cogen													
Location: Brazil, N2O model: IPCC, main references: Damen 2001/JRC 2008 (short term)													
		MJ_p/MJ_f		g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f		g. $CO_{2\text{-}eq}/MJ_f$
Cultivation		0.01		0.8	100%	57%	91%			100%			
N_2O emissions			(0.1)	0.1	100%	57%	91%			100%			
Wood chipping		0.00		0.3	100%	57%	91%			100%			
Road transport, 260 km		0.02		1.2	100%	57%	91%			100%			
Ethanol+ plant		0.06		2.1	100%	57%	91%	-0.12	-7.1	100%	-0.17	-(7.8)	-7.8
Transport to depot		0.03		1.9	100%	100%	100%			100%			
Refuelling station		0.01		0.4	100%	100%	100%			100%			
Total		**0.13**	**(6.8)**	**6.8**									
Yield	GJ/ha*yr^{-1}			405									
Primary fossil energy	MJ_p/MJ_f				**0.13**	**0.09**	**0.12**			**0.01**			**-0.05**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f				**6.8**	**4.9**	**6.4**			**-0.4**			**-1.0**

Table A. 4a
Results: FT-diesel from switchgrass.

	Gross energy requirement and GHG emissions		Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Switchgrass FT-diesel (EU15) excluding pelletization										
Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2004										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.10	9.7	100%	62%	93%			100%		
N_2O emissions		(7.0) 7.0	100%	62%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	62%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	62%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	62%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.17**	**(21.6) 21.6**								
Yield	$GJ/ha*yr^{-1}$	104								
Primary fossil energy	MJ_p/MJ_f		**0.17**	**0.11**	**0.16**			**0.00**		**-0.06**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**21.6**	**13.9**	**20.1**			**12.2**		**11.3**
Switchgrass FT-diesel (East Europe) excluding pelletization										
Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2004										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.10	9.7	100%	93%	93%			100%		
N_2O emissions		(7.0) 7.0	100%	93%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	93%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	93%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	93%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.17**	**(21.6) 21.6**								
Yield	$GJ/ha*yr^{-1}$	104								
Primary fossil energy	MJ_p/MJ_f		**0.17**	**0.16**	**0.16**			**0.00**		**-0.06**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**21.6**	**20.1**	**20.1**			**12.2**		**11.3**
Switchgrass FT-diesel (EU15) excluding pelletization										
Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2030										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.07	5.3	100%	93%	93%			100%		
N_2O emissions		(7.0) 7.0	100%	93%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	93%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	93%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	93%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.14**	**(17.2) 17.2**								
Yield	$GJ/ha*yr^{-1}$	147								
Primary fossil energy	MJ_p/MJ_f		**0.14**	**0.13**	**0.13**			**-0.02**		**-0.09**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**17.2**	**16.0**	**16.0**			**7.7**		**6.8**
Switchgrass FT-diesel (East Europe) excluding pelletization										
Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2030										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.07	5.1	100%	93%	93%			100%		
N_2O emissions		(7.0) 7.0	100%	93%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	93%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	93%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	93%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.14**	**(17.0) 17.0**								
Yield	$GJ/ha*yr^{-1}$	159								
Primary fossil energy	MJ_p/MJ_f		**0.14**	**0.13**	**0.13**			**-0.02**		**-0.09**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**17.0**	**15.8**	**15.8**			**7.6**		**6.7**

Table A. 4b
Results: FT-diesel from miscanthus.

	Gross energy requirement and GHG emissions		Allocation (%) Mass	MV	Energy	EU approach Co-gen. credits		Co-prod.	System expansion Credits	
Miscanthus FT-diesel (EU15) excluding pelletization										
Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2004										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.09	7.4	100%	62%	93%			100%		
N_2O emissions		(3.5) 3.5	100%	62%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	62%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	62%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	62%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.16**	**(15.8) 15.8**								
Yield	GJ/ha*yr^{-1}	130								
Primary fossil energy	MJ_p/MJ_f		**0.16**	**0.10**	**0.15**			**-0.01**		**-0.07**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**15.8**	**10.3**	**14.7**			**6.4**		**5.4**
Miscanthus FT-diesel (East Europe) excluding pelletization										
Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2004										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.08	7.2	100%	93%	93%			100%		
N_2O emissions		(3.5) 3.5	100%	93%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	93%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	93%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	93%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.15**	**(15.6) 15.6**								
Yield	GJ/ha*yr^{-1}	138								
Primary fossil energy	MJ_p/MJ_f		**0.15**	**0.14**	**0.14**			**-0.01**		**-0.08**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**15.6**	**14.5**	**14.5**			**6.2**		**5.3**
Miscanthus FT-diesel (EU15) excluding pelletization										
Location: EU15, N2O model: IPCC, main references: Smeets et al. 2008, 2030										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.06	4.4	100%	93%	93%			100%		
N_2O emissions		(3.5) 3.5	100%	93%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	93%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	93%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	93%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.13**	**(12.8) 12.8**								
Yield	GJ/ha*yr^{-1}	1								
Primary fossil energy	MJ_p/MJ_f		**0.13**	**0.13**	**0.13**			**-0.03**		**-0.10**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**12.8**	**12.0**	**12.0**			**3.4**		**2.5**
Miscanthus FT-diesel (East Europe) excluding pelletization										
Location: East Europe, N2O model: IPCC, main references: Smeets et al. 2008, 2030										
	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation	0.06	4.2	100%	93%	93%			100%		
N_2O emissions		(3.5) 3.5	100%	93%	93%			100%		
Road transport, 100 km	0.01	0.6	100%	93%	93%			100%		
Bulk inland carrier, 400 km	0.02	1.7	100%	93%	93%			100%		
BTL plant (FT-diesel)	0.02	1.5	100%	93%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot	0.01	0.7	100%	100%	100%			100%		
Refuelling station	0.01	0.4	100%	100%	100%			100%		
Total	**0.13**	**(12.6) 12.6**								
Yield	GJ/ha*yr^{-1}	199								
Primary fossil energy	MJ_p/MJ_f		**0.13**	**0.12**	**0.12**			**-0.03**		**-0.10**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f		**12.6**	**11.8**	**11.8**			**3.2**		**2.3**

Table A. 4c
Results: FT-diesel from eucalyptus.

		Gross energy requirement and GHG emissions		Allocation (%)			EU approach			System expansion	
				Mass	MV	Energy	Co-gen. credits		Co-prod.	Credits	
Eucalyptus FT-diesel (Brazil) FT-synthesis with co-gen. Location: Brazil, N2O model: IPCC, main references: Damen 2001/JRC 2008 (short term)											
		MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	%	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$	%	MJ_p/MJ_f	g. $CO_{2\text{-}eq}/MJ_f$
Cultivation		0.02	1.8	100%	62%	93%			100%		
N_2O emissions			(0.2) 0.2	100%	62%	93%			100%		
Wood chipping		0.01	0.8	100%	62%	93%			100%		
Road transport, 260 km		0.04	2.7	100%	62%	93%			100%		
BTL plant (FT-diesel)		0.00	0.0	100%	62%	93%	-0.16	-9.4	100%	-0.23	-(10.3) -10.3
Transport to depot		0.05	3.8	100%	100%	100%			100%		
Refuelling station		0.01	0.4	100%	100%	100%			100%		
Total		**0.13**	**(9.8) 9.8**								
Yield	GJ/ha*yr^{-1}		171								
Primary fossil energy	MJ_p/MJ_f			**0.13**	**0.11**	**0.13**			**-0.03**		**-0.09**
Net GHG emissions (IPCC)	g. CO2-eq/MJ_f			**9.8**	**7.7**	**9.4**			**0.4**		**-0.5**

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